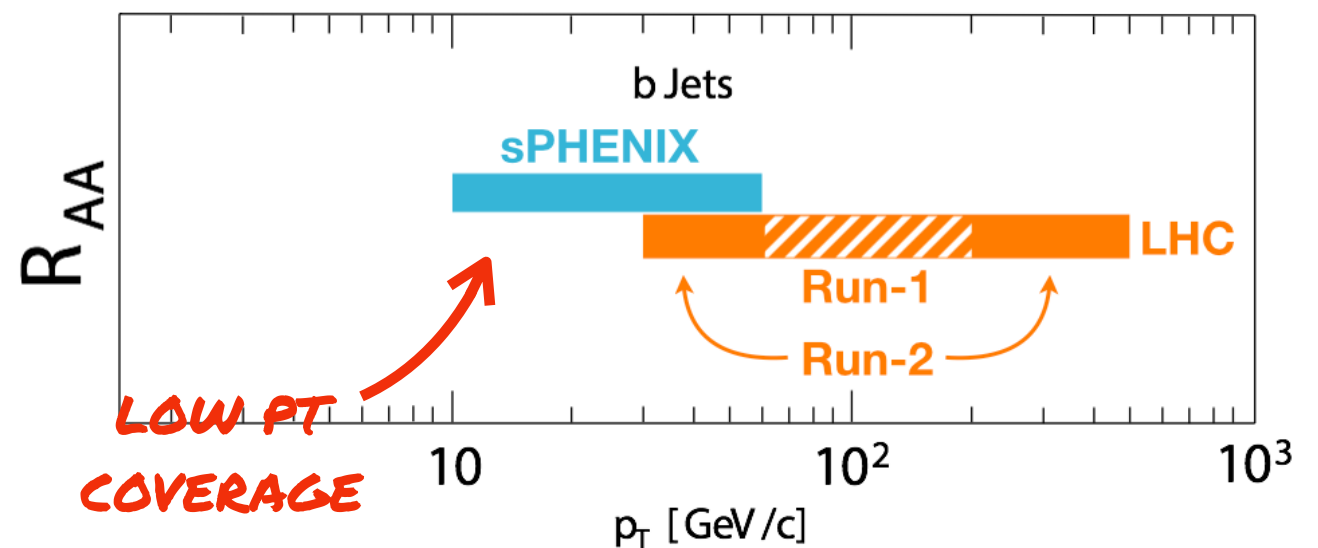
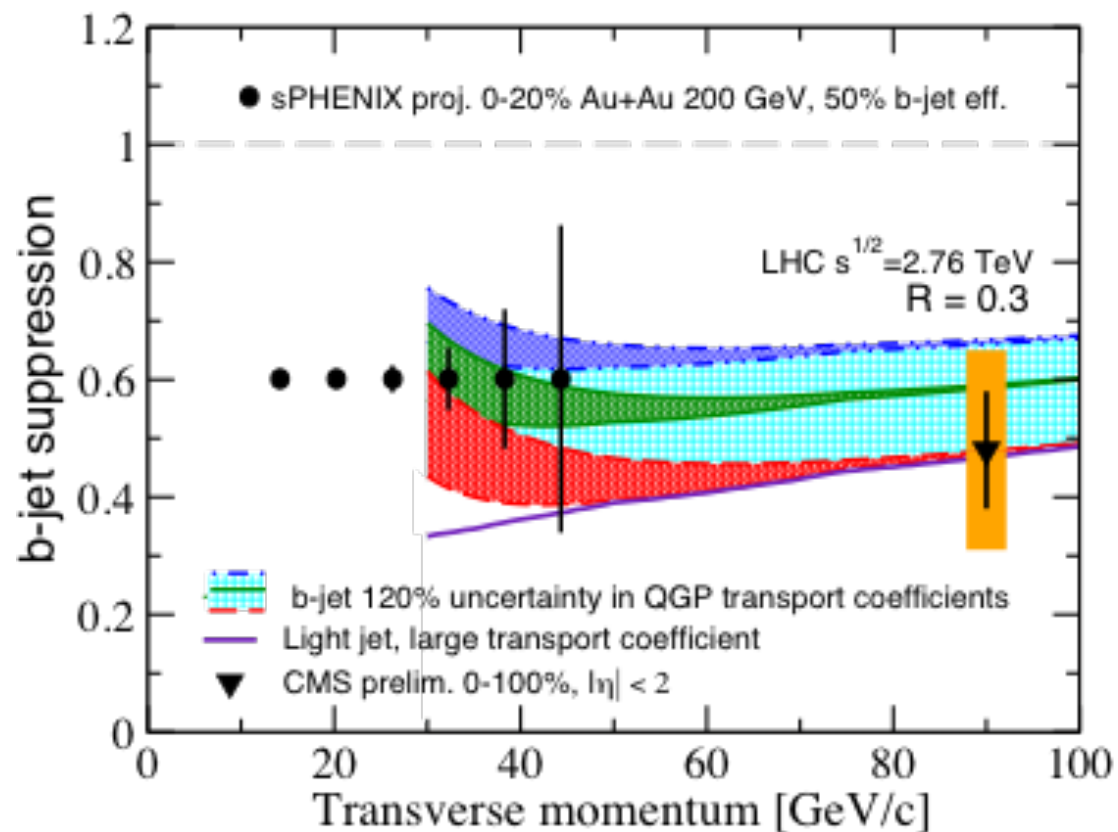
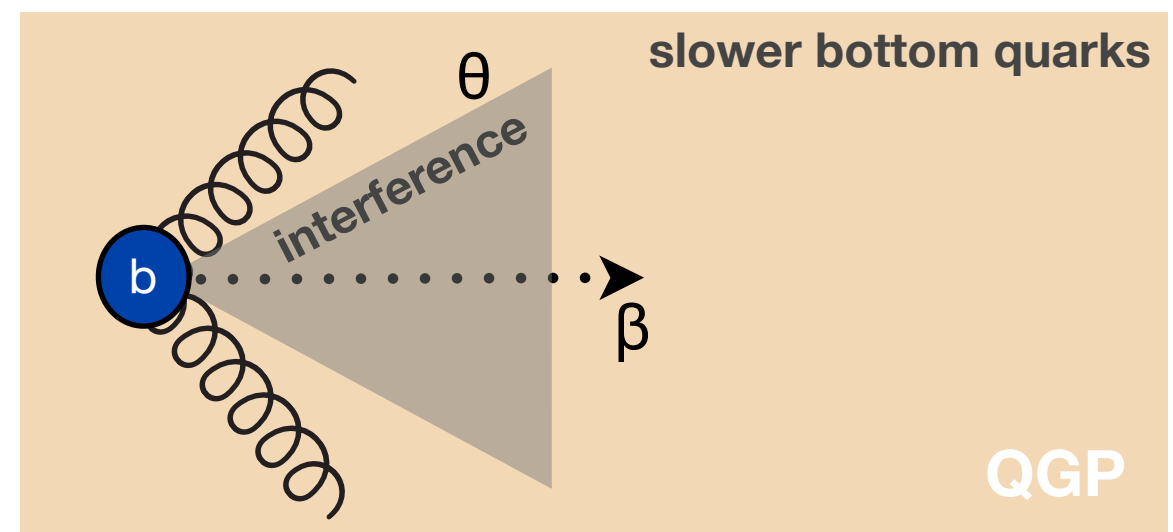
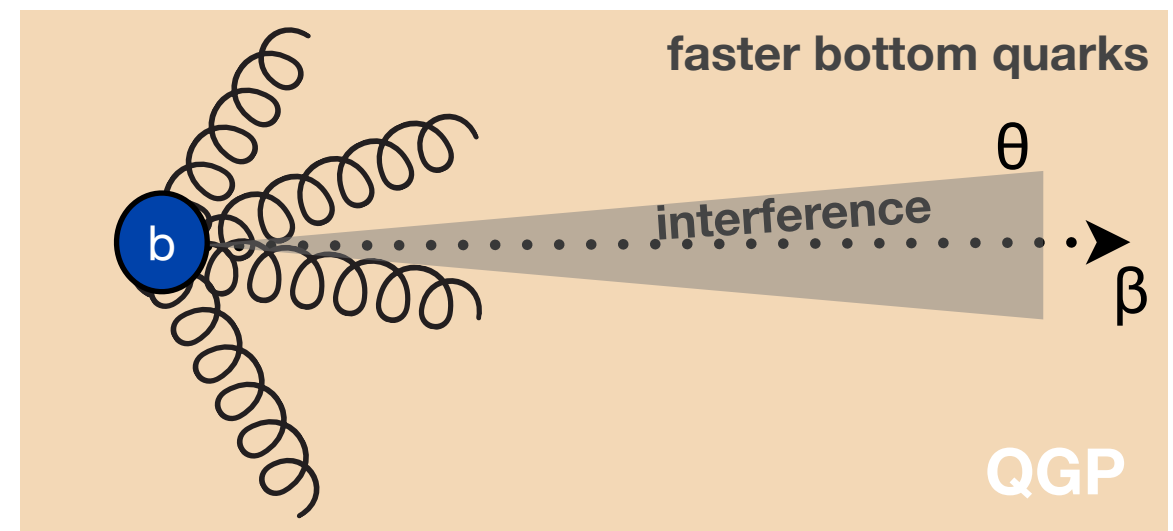
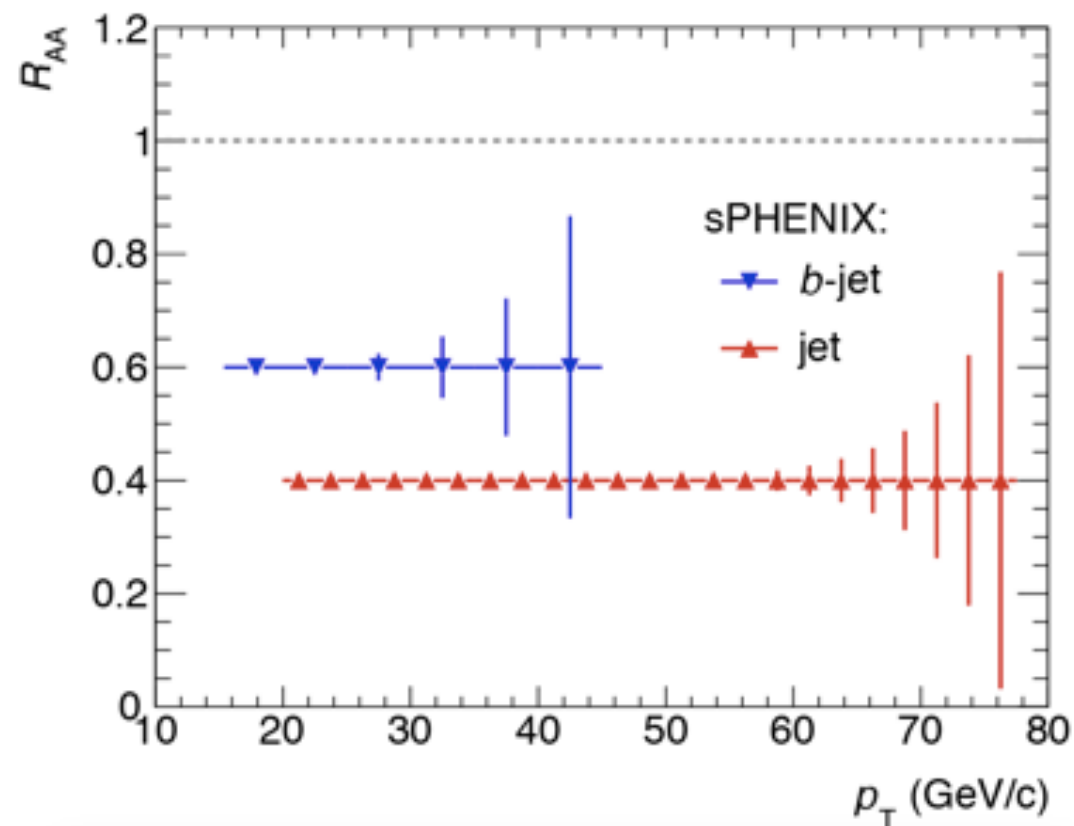


# ***Heavy Flavor Jet Physics and Topical Group Status***

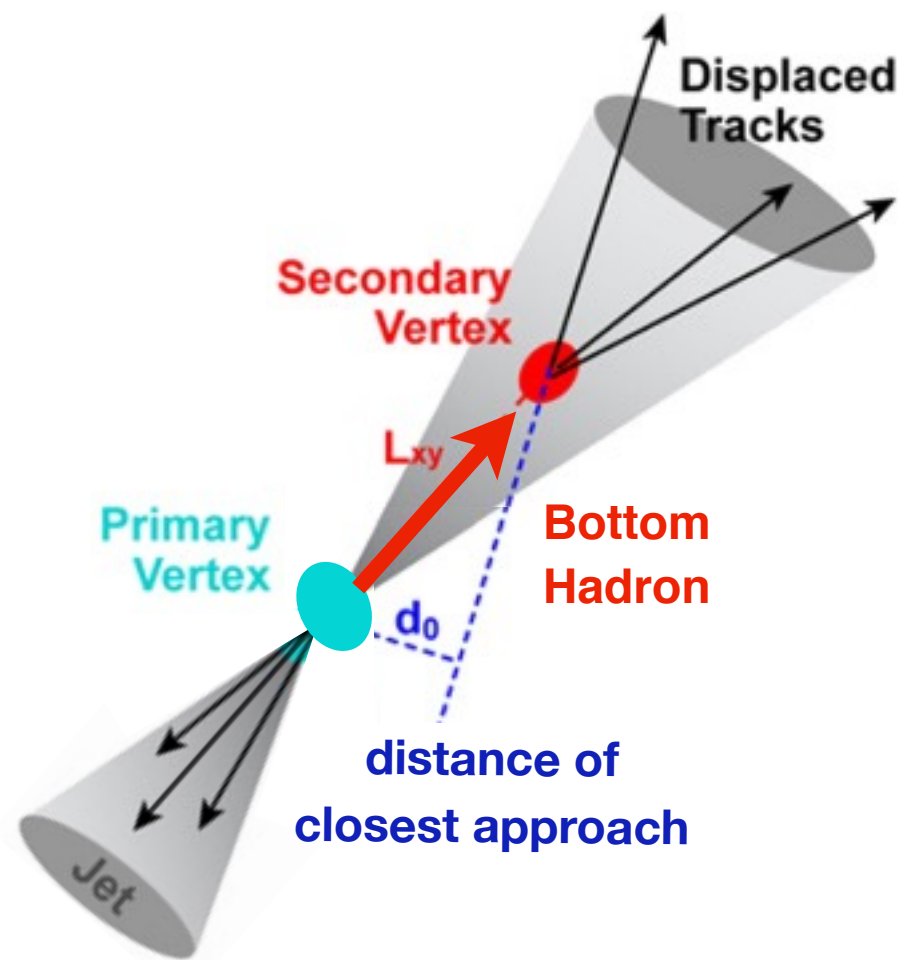
**Michael P. McCumber**  
Heavy Flavor Jet Workshop  
Brookhaven National Lab  
May 16 2016

# B-jet Physics: Energy Loss





# B-jet Identification Methodology



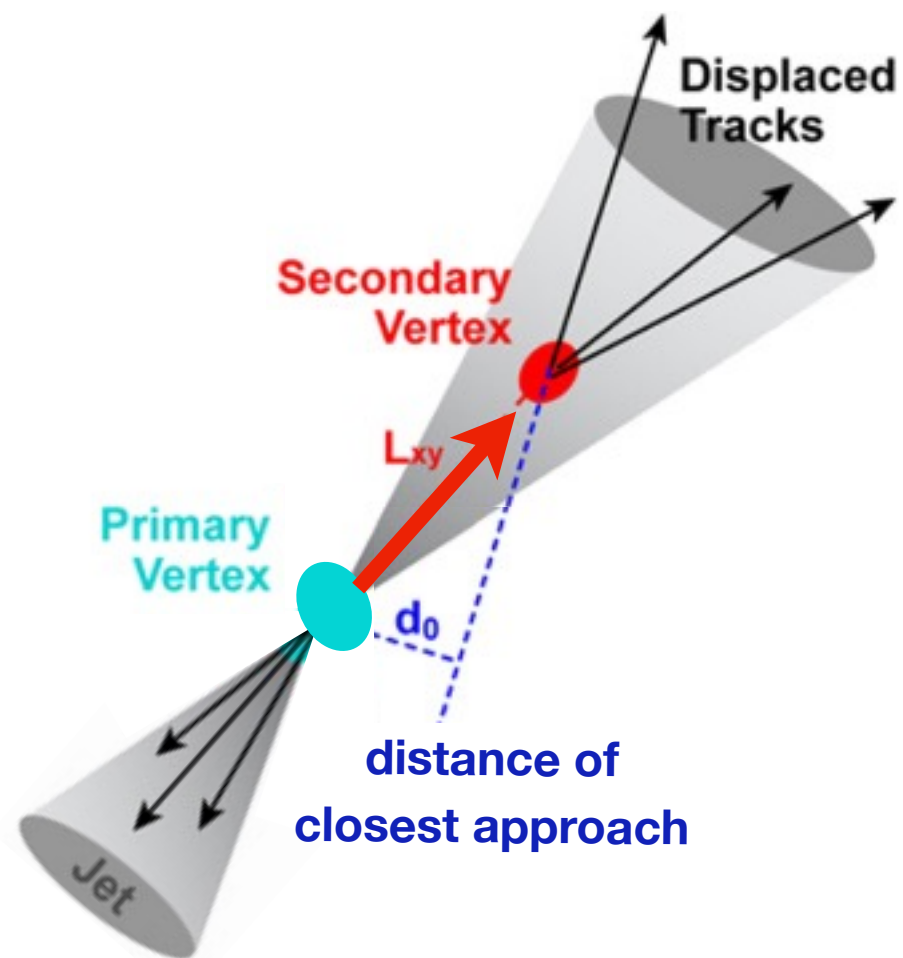
sPHENIX should have access to 3 different techniques for heavy-flavor identification:

- (1) Semi-leptonic decay
- (2) Multiple Large DCA tracks
- (3) Secondary Vertex Mass

Big push from DVP  
for sPHENIX proposal

Unexplored thus far!

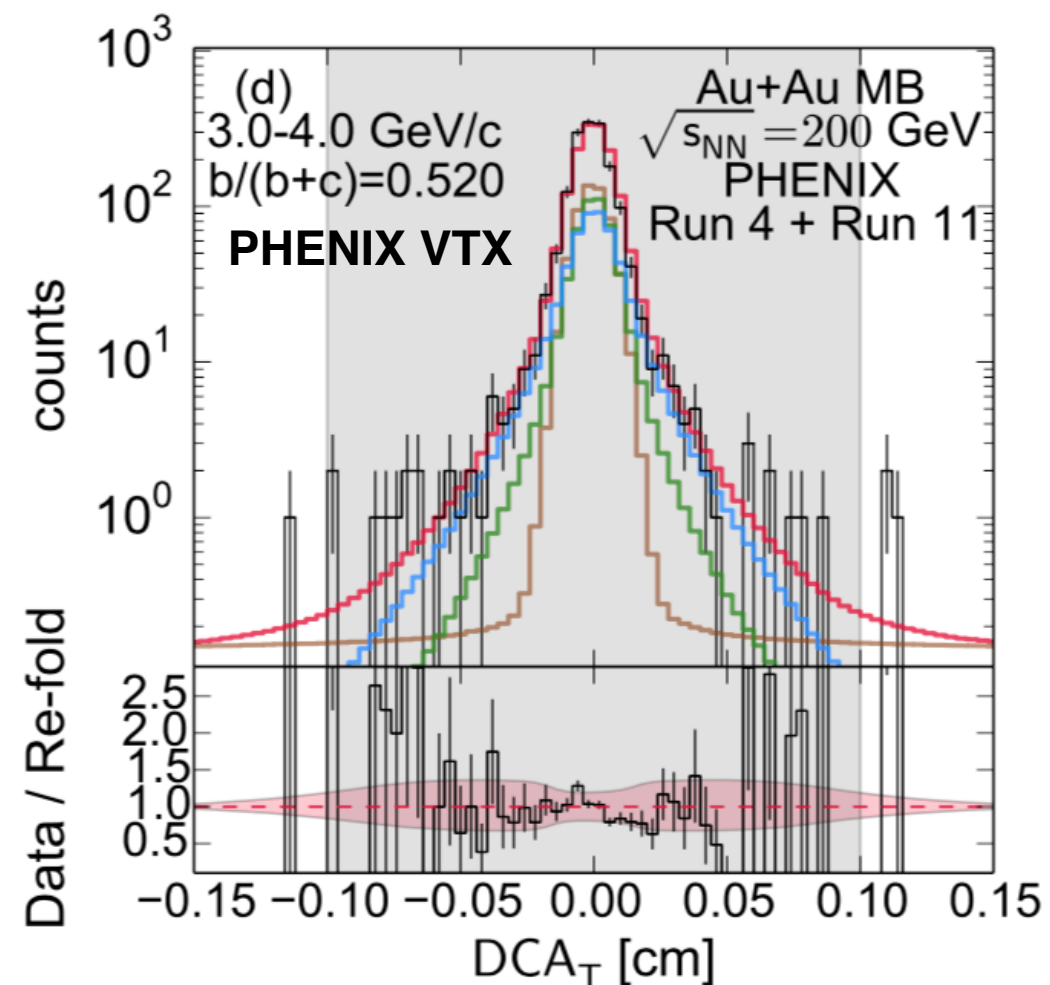
# B-jet Identification Methodology



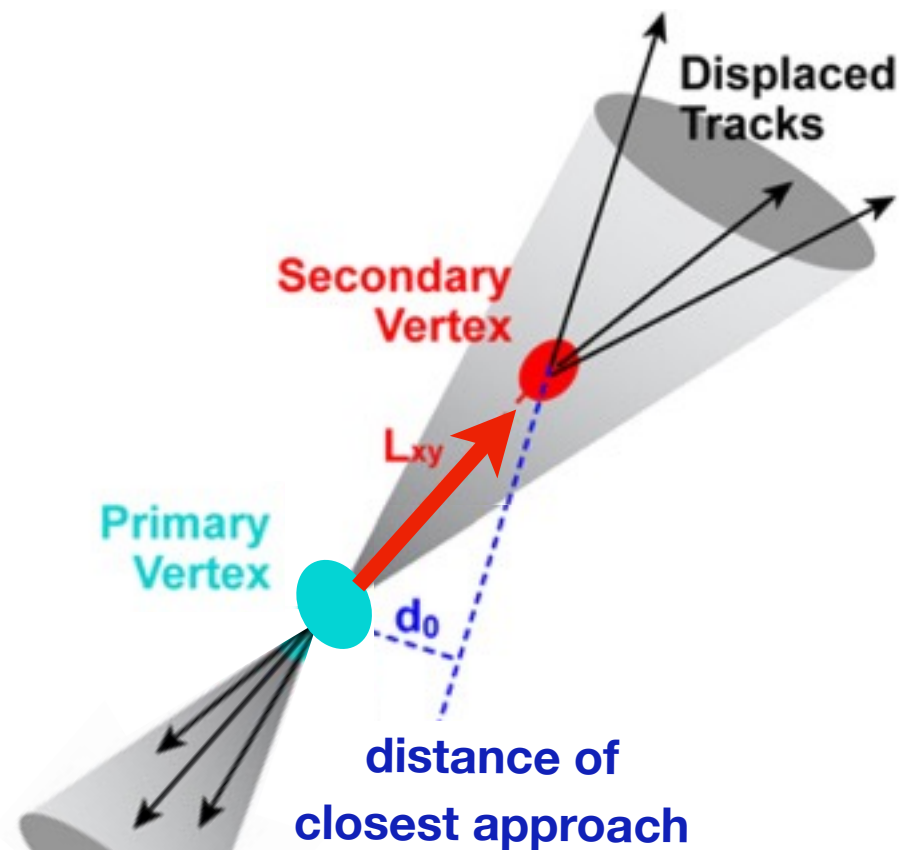
Semi-leptonic decay requirements:  
 Electron identification at large  $p_T$   
 Narrow primary electron DCA distribution

sPHENIX should have access to 3 different techniques for heavy-flavor identification:

- (1) Semi-leptonic decay
- (2) Multiple Large DCA tracks
- (3) Secondary Vertex Mass



# B-jet Identification Methodology



Semi-leptonic decay requirements:

Electron identification at large  $p_T$

Narrow primary electron DCA distribution

Downsides: Large reduction (x20) in B-jets if only the semi-leptonic decay channel is used.  
Hadron rejection needed could be  $\sim 1000:1$

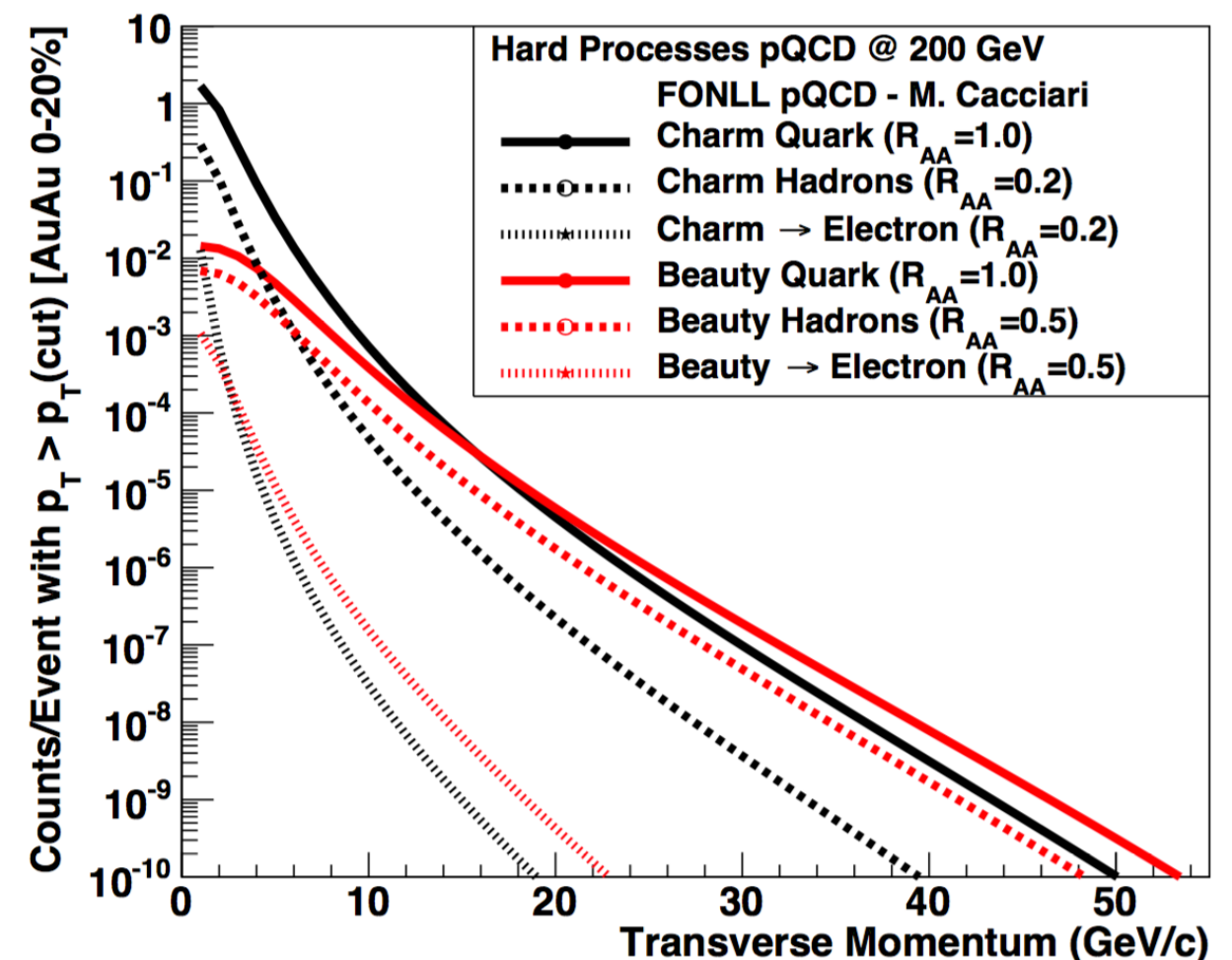
*Unclear if this is a viable route to b-jets*

sPHENIX should have access to 3 different techniques for heavy-flavor identification:

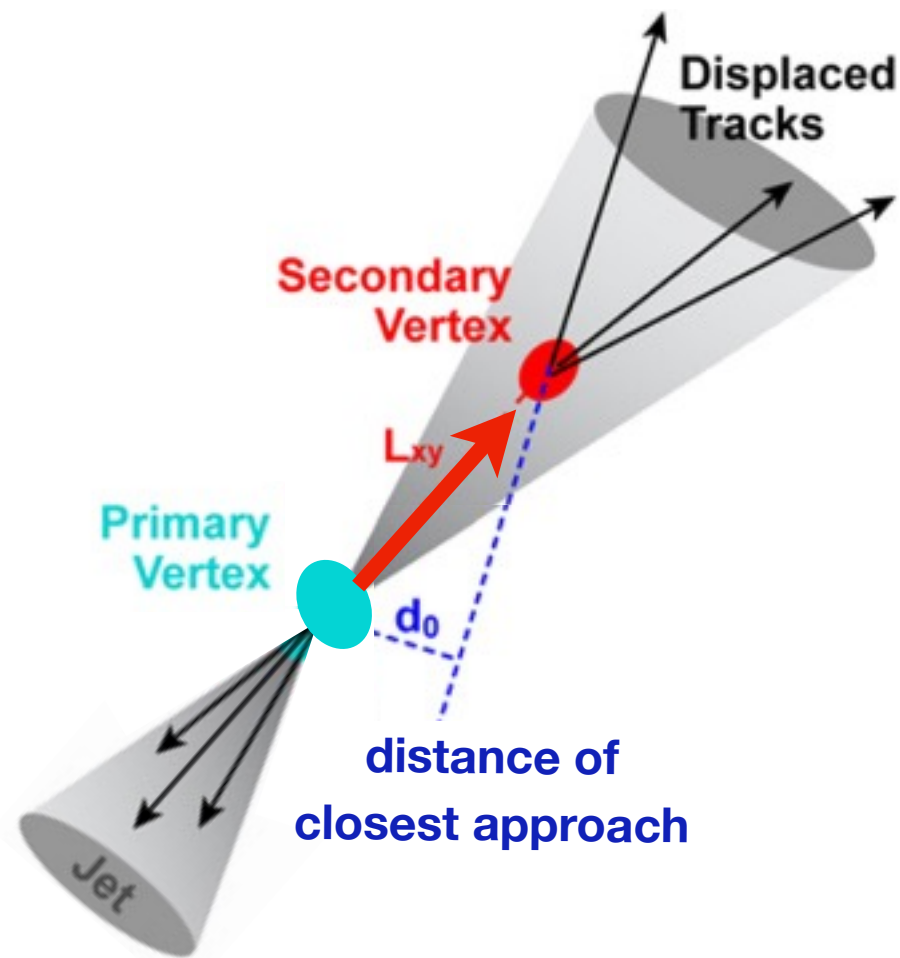
(1) Semi-leptonic decay

(2) Multiple Large DCA tracks

(3) Secondary Vertex Mass



# B-jet Identification Methodology



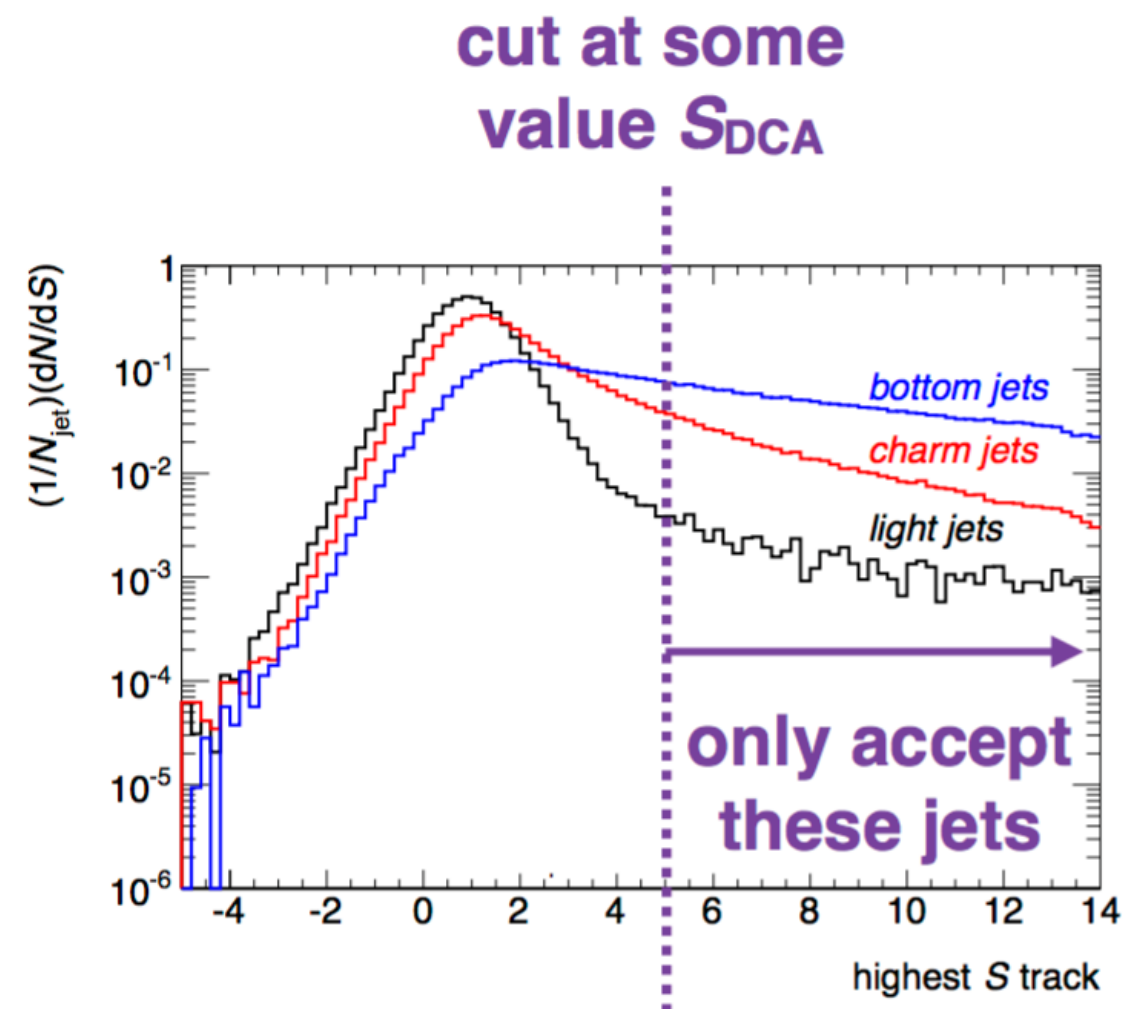
sPHENIX should have access to 3 different techniques for heavy-flavor identification:

- (1) Semi-leptonic decay
- (2) Multiple Large DCA tracks**
- (3) Secondary Vertex Mass

Track Counting requirements:

Large single particle reconstruction efficiency,  $\sim \epsilon^N$

Narrow primary hadron DCA distribution ( $< 70 \mu\text{m}$ )



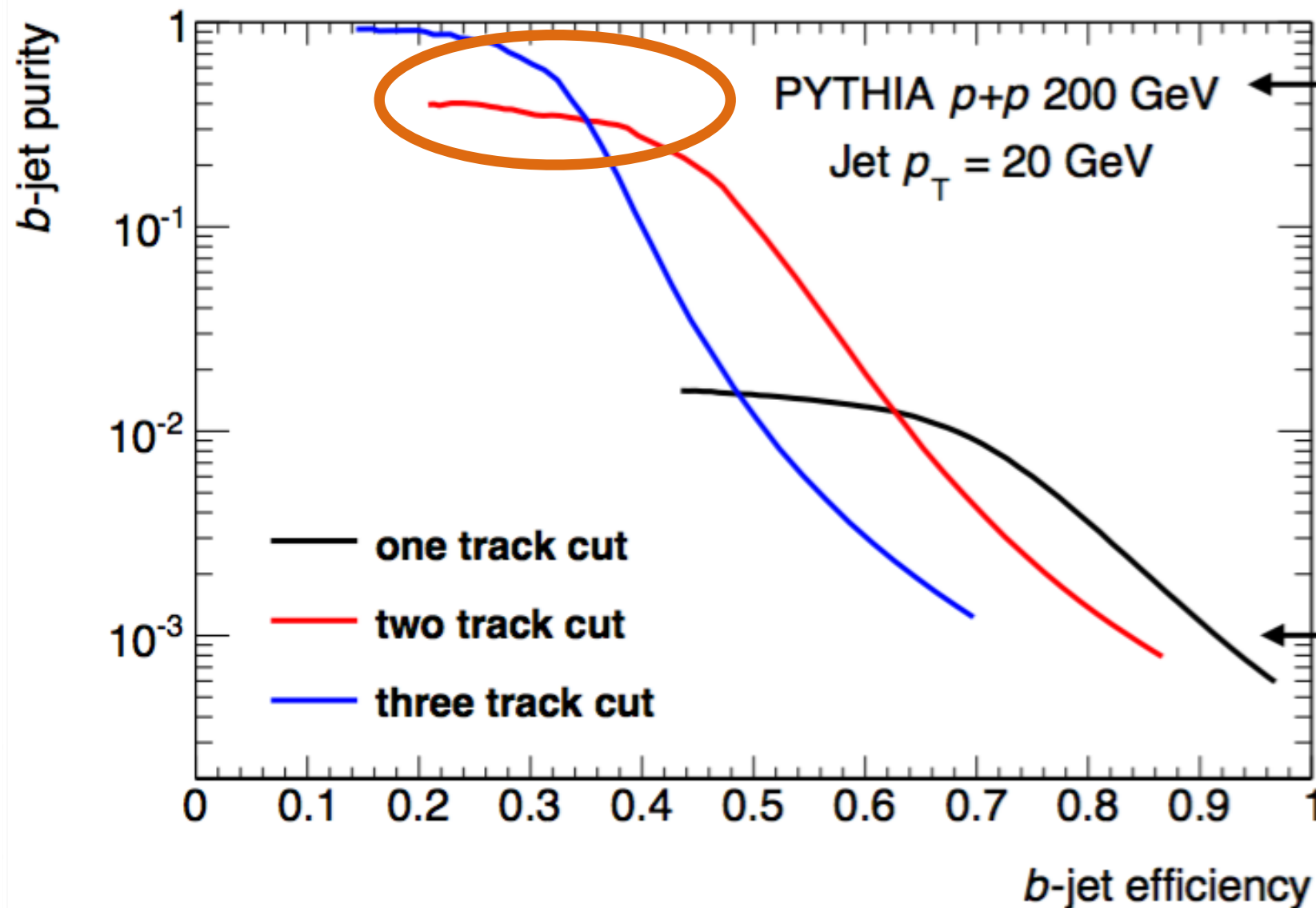


# B-jet Identification Methodology

7

from the April Review...

## $b$ -jet performance in $p+p$



Purity  $\sim 0.5$  is achievable at reasonable efficiency!

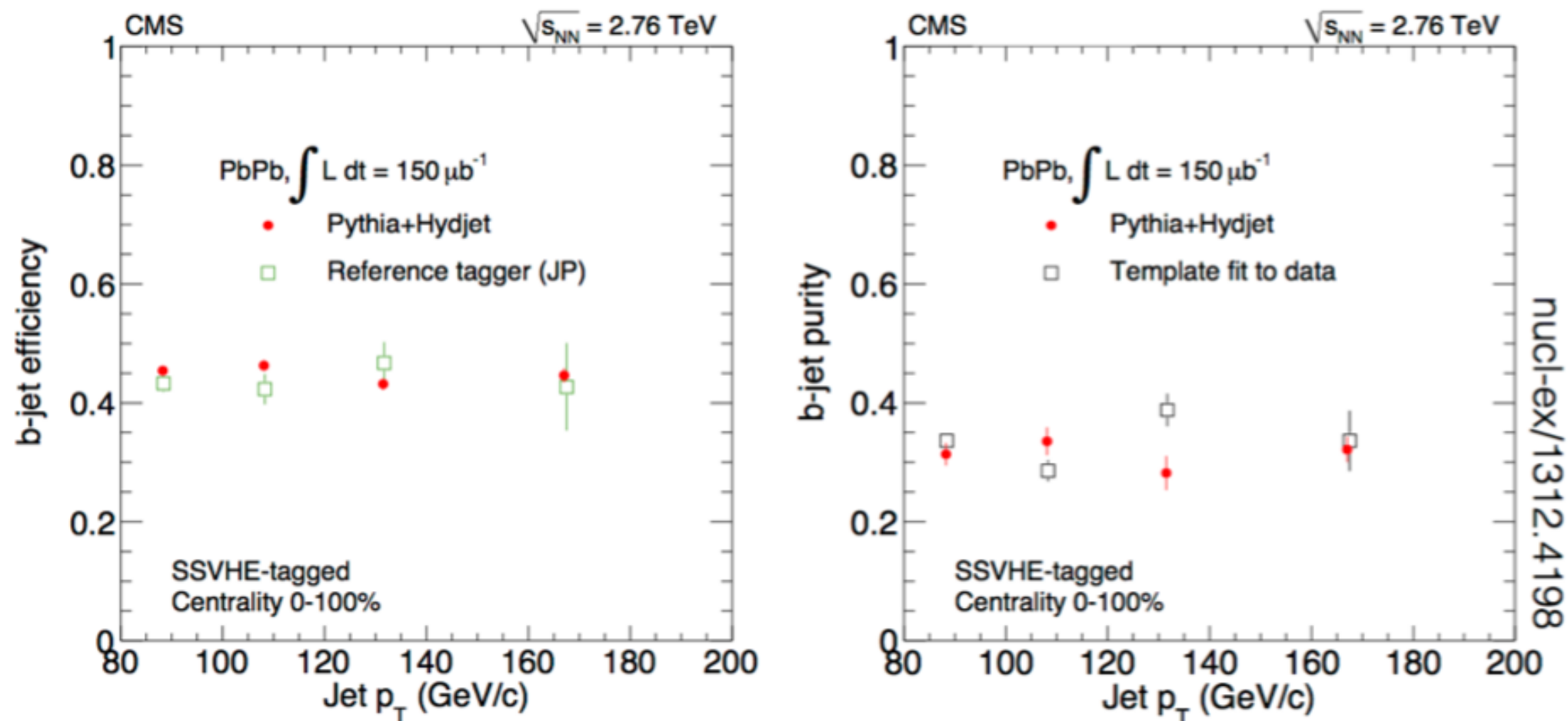
Purity  $< 10^{-3}$  before any cuts!

**P** vs. **E** curves for requiring **1**, **2** or **3** tracks with  $S_{DCA}$  above some minimum value

# CMS b-jet Performance

from the April Review...

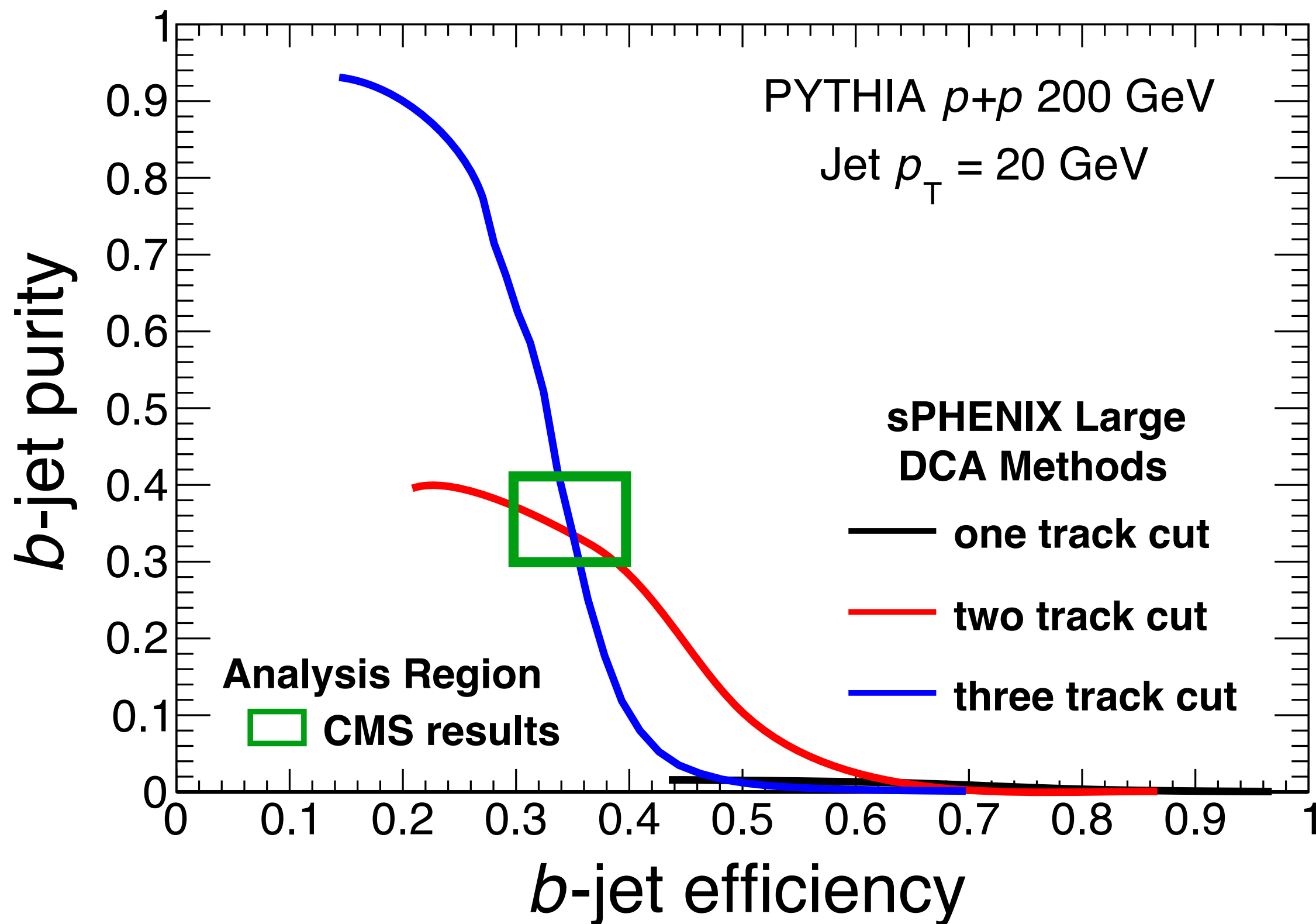
## *b*-jet efficiency and purity in Pb+Pb



$\approx 45\%$  Efficiency and  $\approx 35\%$  Purity in the CMS *b*-jet spectrum in Pb+Pb

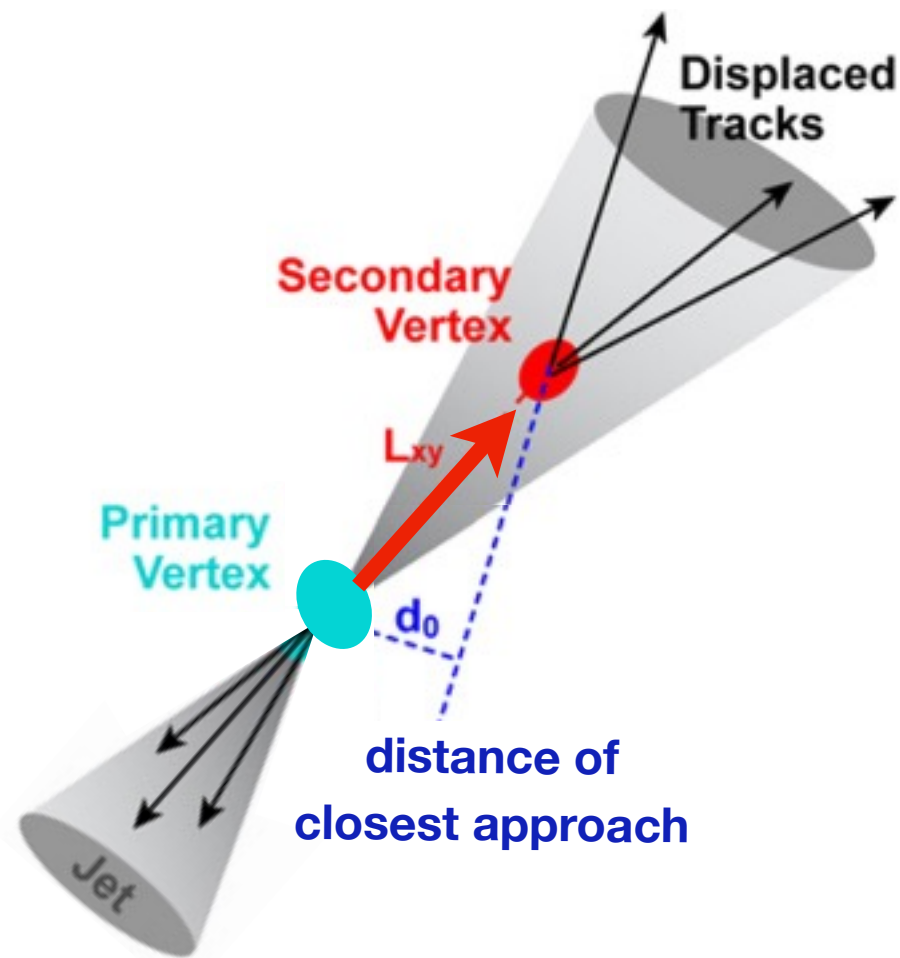
→ comparable to that achievable with 2- or 3-track TrackCounting cuts

# CMS b-jet Performance



NB: under the assumption of 100% single particle efficiency!!!

# B-jet Identification Methodology



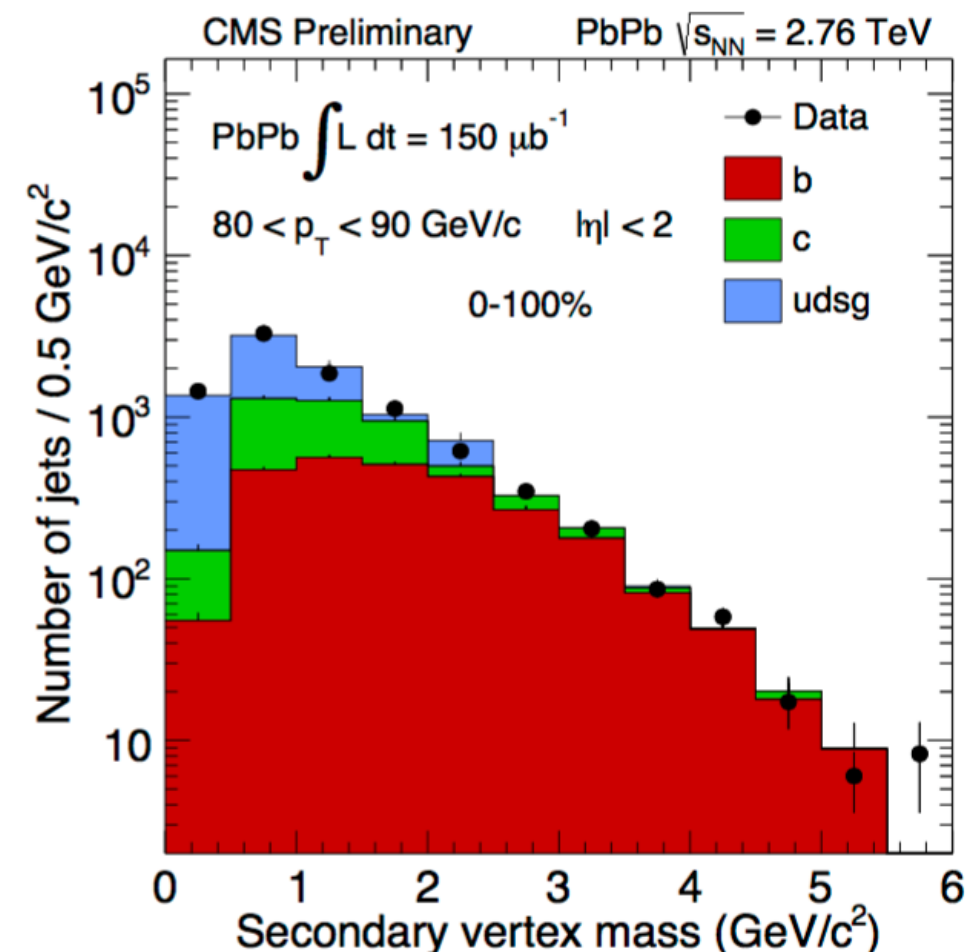
Secondary Vertex requirements:

Large single particle reconstruction efficiency,  $\sim \epsilon^2$

Individual track position resolution

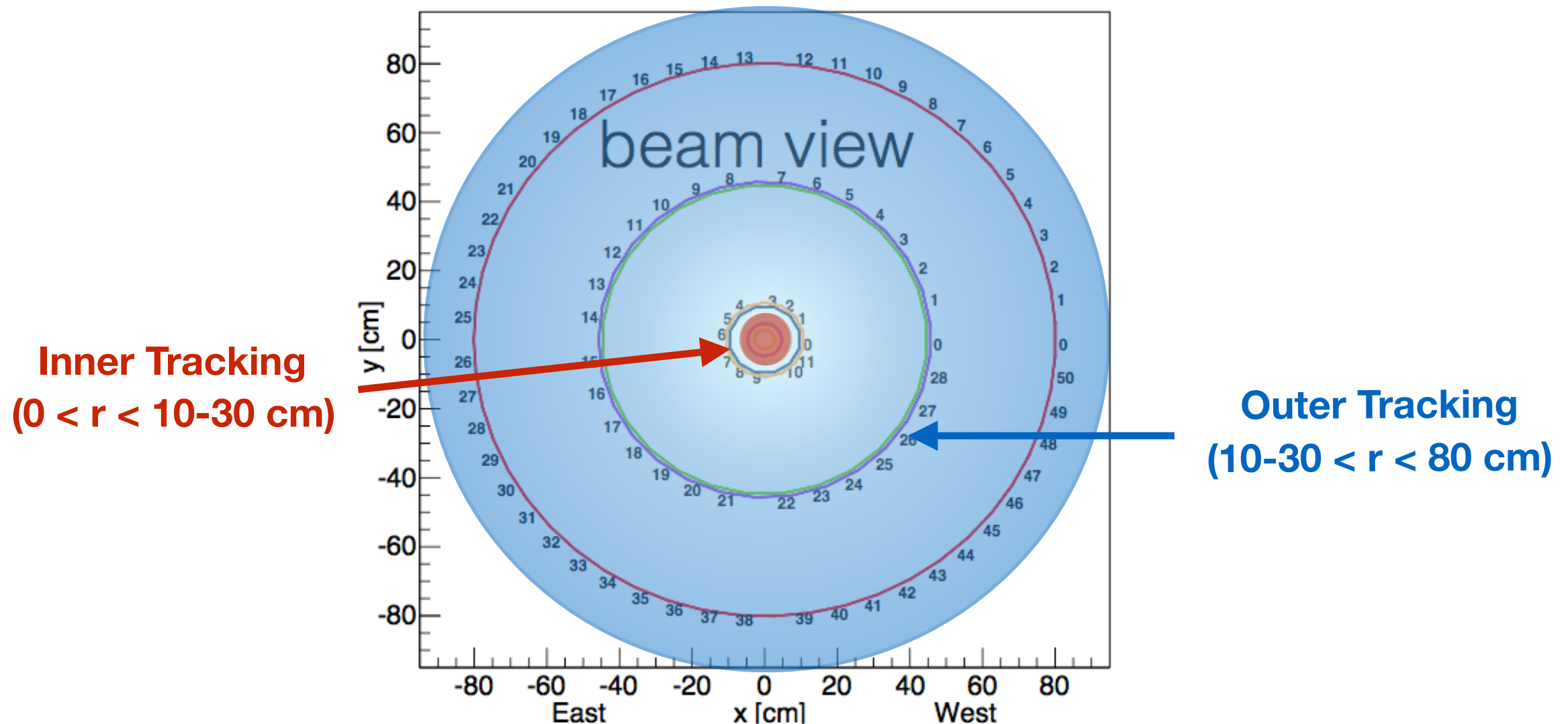
sPHENIX should have access to 3 different techniques for heavy-flavor identification:

- (1) Semi-leptonic decay
- (2) Multiple Large DCA tracks
- (3) Secondary Vertex Mass**





# Partial Factorization: Tracking Goals



## Inner tracking:

- (1) precision track position  
(DCA, 2nd vertexing)
- (2) high resolution collision vertexing
- (3) *pattern recognition ambiguity breaking*

## Outer tracking:

- (1) momentum resolution optimization
- (2) *pattern recognition ambiguity breaking*

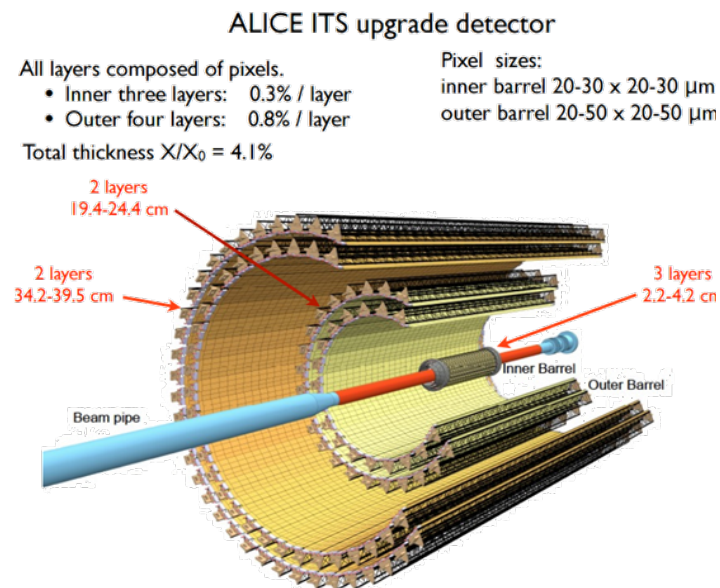
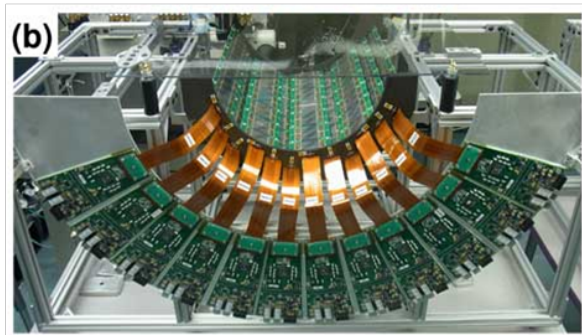
# Tracking Tech Down-Select

We have four technology options...

- ▶ Inner Vertex Detector ( $\sigma_{DCA} < 100 \mu m$ )
  - ▶ Reuse existing PHENIX VTX pixel detector.
  - ▶ MAPS Technology (e.g. ALICE ITR Upgrade)
- ▶ Outer Tracker ( $\sigma_m < 100 \frac{MeV}{c^2} @ 9 \frac{GeV}{c^2}$ )
  - ▶ Silicon Strip Detector
  - ▶ Non-gated TPC (Hybrid means TPC+reuse)

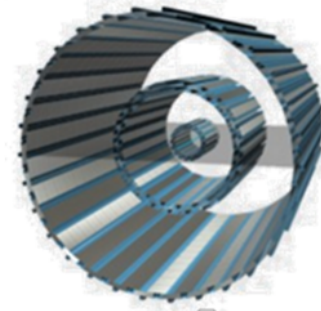
## Reuse PHENIX VTX Components

- Momentum Resolution Limited by Multiple Scattering.
- Significant Dead Area (non-working & gaps)



## New PHENIX-like Components

- Straightforward technology.
- Fast (no event pileup).
- Multiple-Scat limited.
- Little PID capability



## Compact TPC (ala ALICE?)

- Higher momentum resolution
- Smaller Bremsstrahlung tails.
- Leverage ALICE R&D
- PID via  $dE/dx$  & neutral V's.

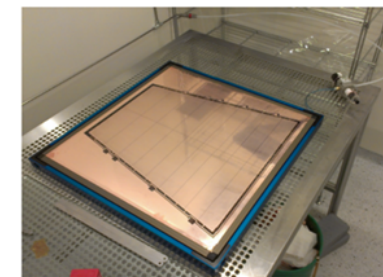


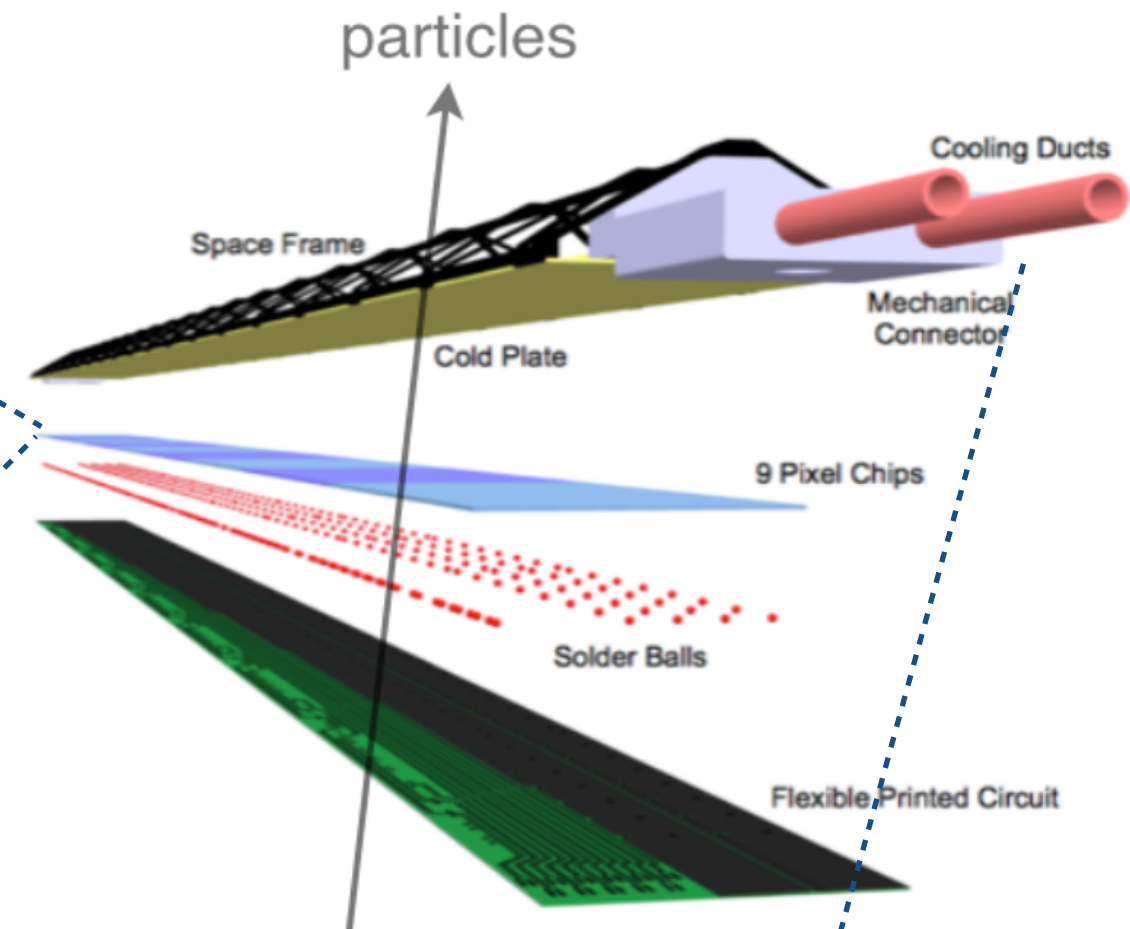
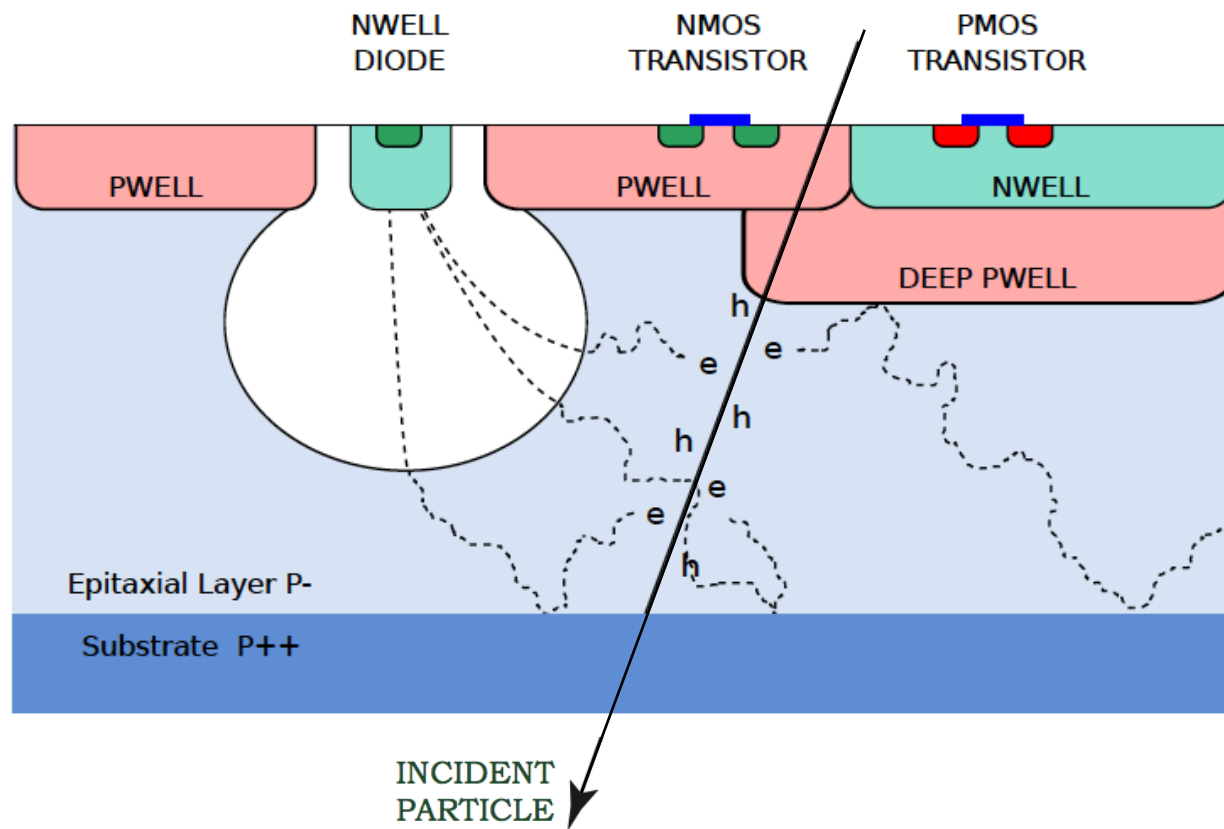
Figure 4.7: Photograph of an BRCC GEM foil in the stretching frame.

Cover electrode	$E_{\text{top}}$
GEM 1	$E_{11}$
GEM 2	$E_{12}$
GEM 3	$E_{13}$
GEM 4	$E_{14}$
Pad plane	readout anode
Strong back	

NOTE: Existing PHENIX pixel detector currently achieves 70  $\mu m$  DCA resolution. MAPS technology would only improve this due to smaller pixels and less material.

Comparison requires detailed simulation.

# Inner Tracking with MAPS sensors



## Inner Silicon Concept:

Thin, fine pitch ( $<30 \mu\text{m}$ ), large efficiency (99.9...%)

Optimizations for material thickness,  $\sim 0.3\%/ \text{layer}$

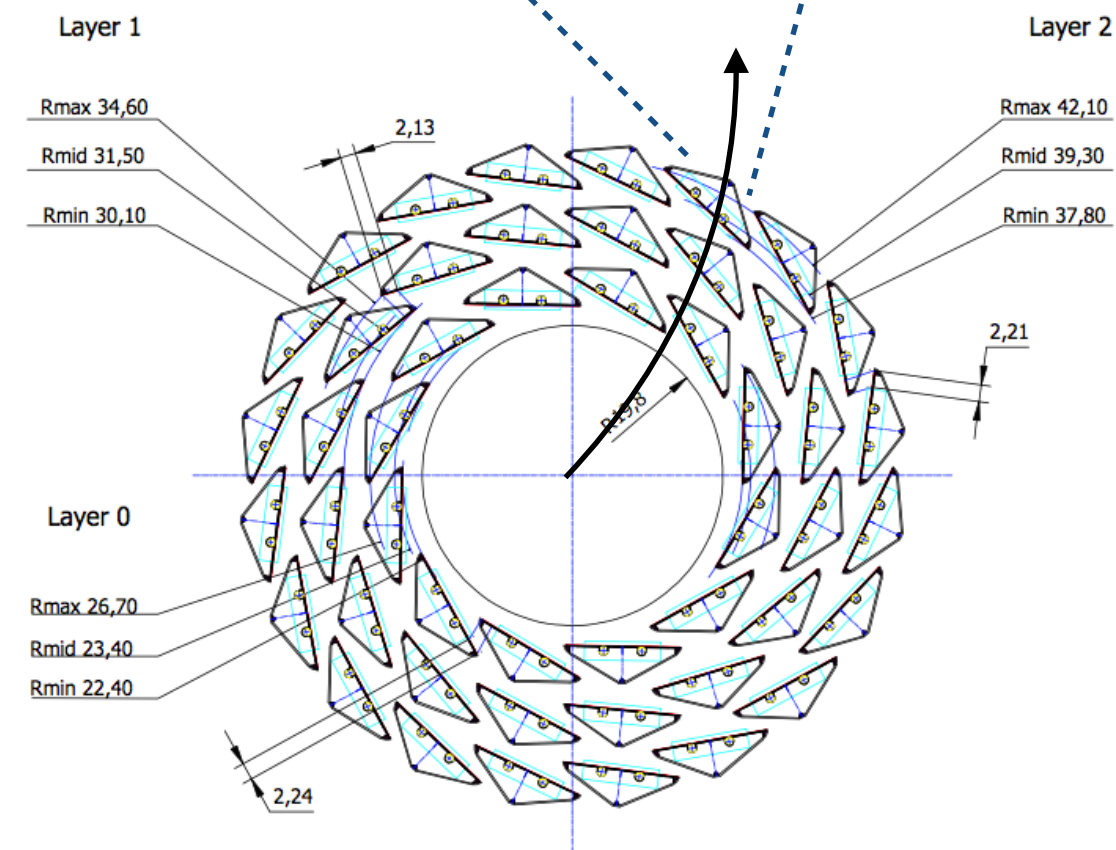
Integration time:  $\sim 2\text{-}4 \mu\text{s}$

## Goal:

Precision tracking & vertexing for b-jet identification and other tracking duties

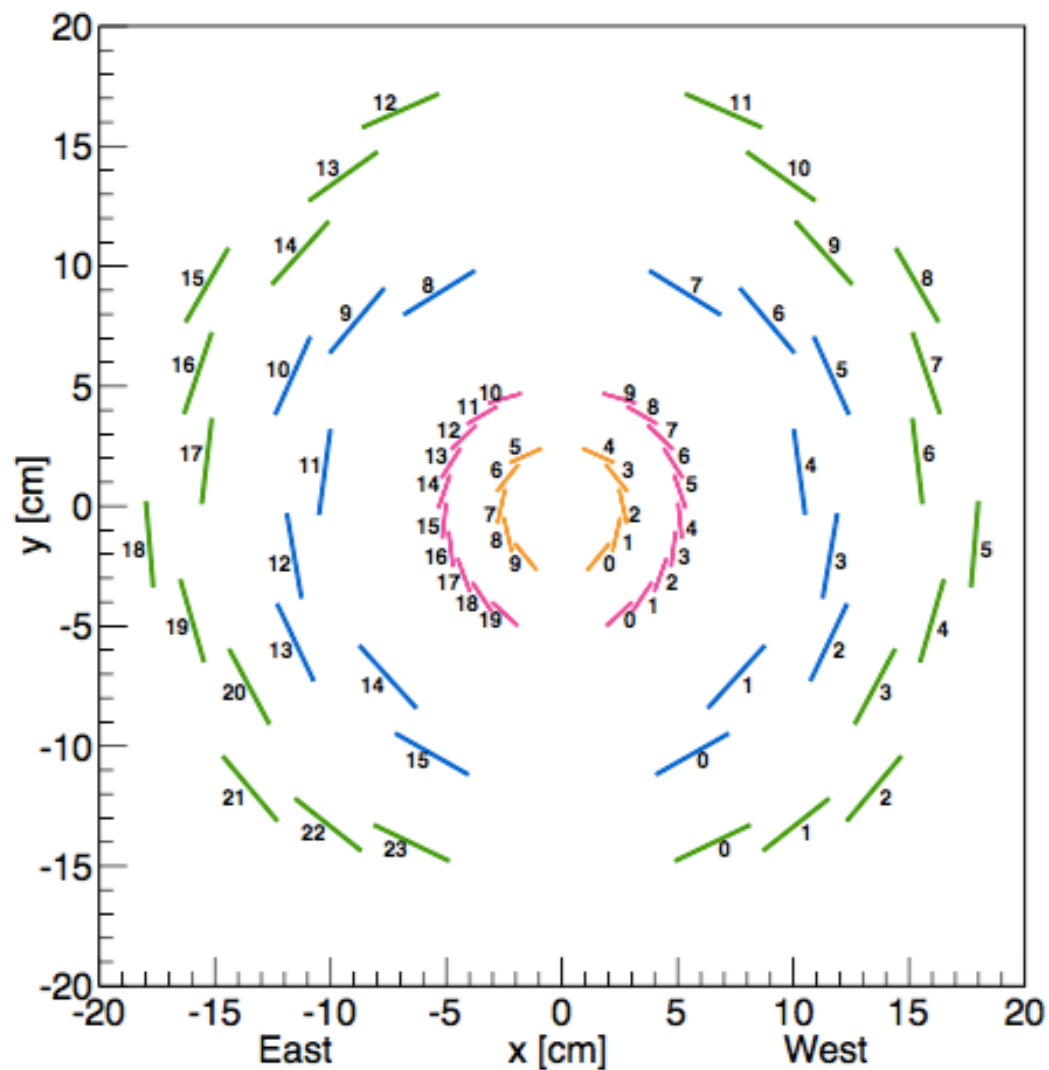
## Opportunity:

Reuse thin inner tracking layers during the EIC era

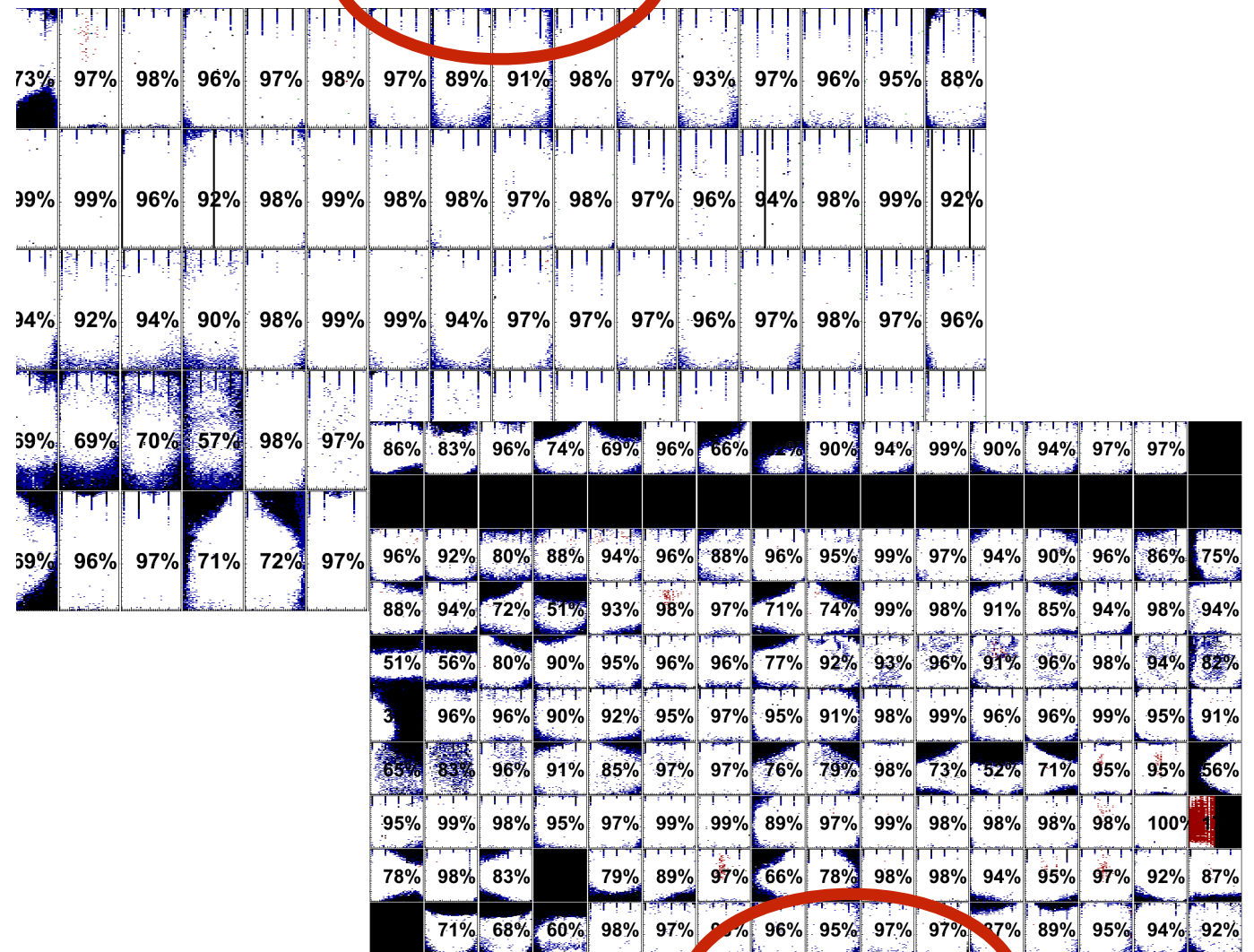




# Tracking Option: Pixels



Pixel Layer 1, 92.5% Active



Pixel Layer 2, 72.5% Active

Station	Layer	radius (cm)	pitch ( $\mu\text{m}$ )	sensor length (cm)	depth ( $\mu\text{m}$ )	total thickness $X_0\%$	area ( $\text{m}^2$ )
Pixel	1	2.4	50	0.425	200	1.3	0.034
Pixel	2	4.4	50	0.425	200	1.3	0.059
S0a	3	7.5	58	9.6	240	1.0	0.18

# Heavy Flavor Topical Group

~~Two~~ Three tasks for our group ...

(1) **Short-term:** Calculate on the physics performance of various (defined) configurations for the ALD Charge

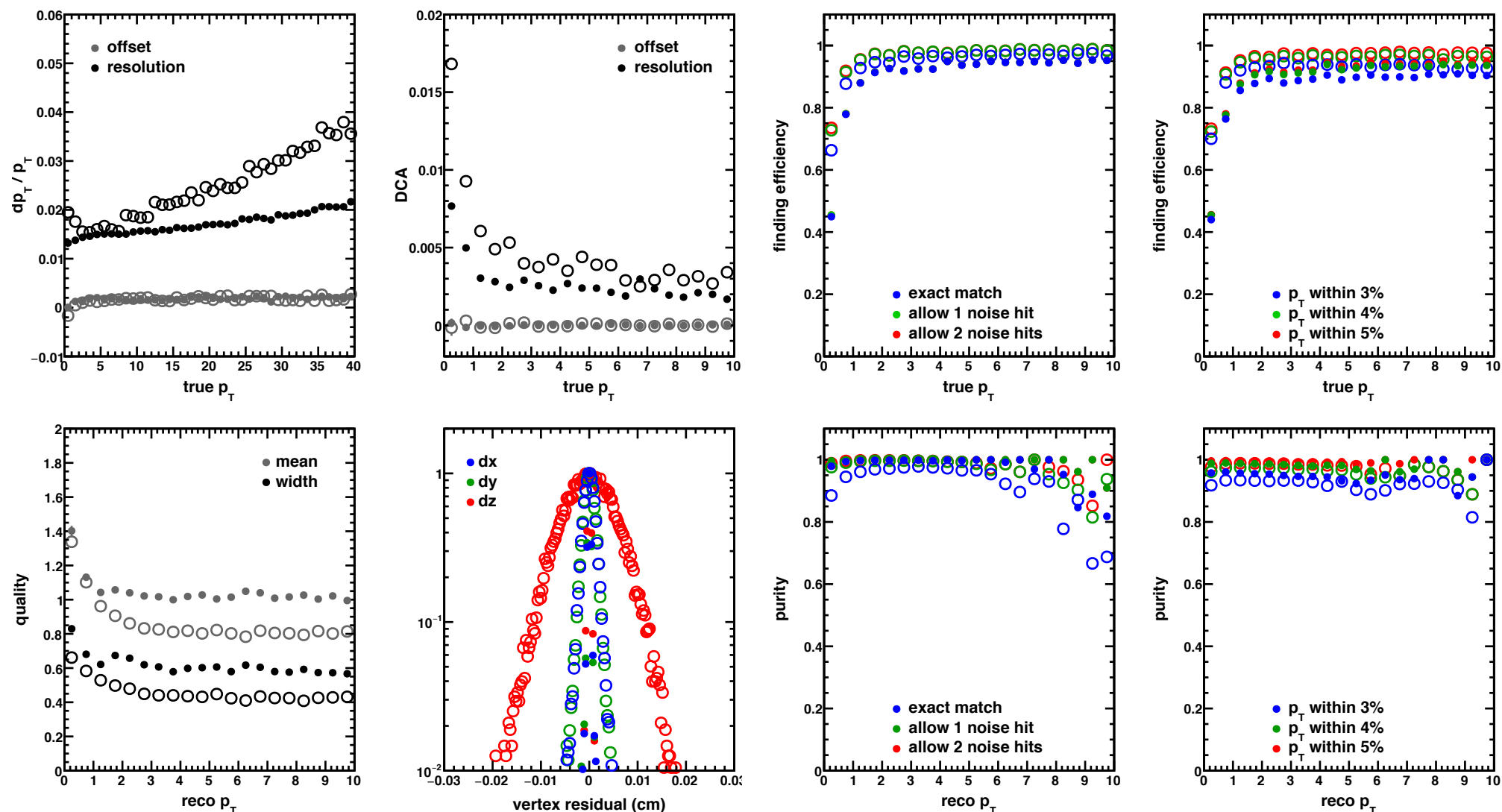
(2) **Longer-term:** Prepare for full-fledged detector simulations

(3) **Immediate-term: restore our simplified detector simulation capabilities**

# Short Term Effort

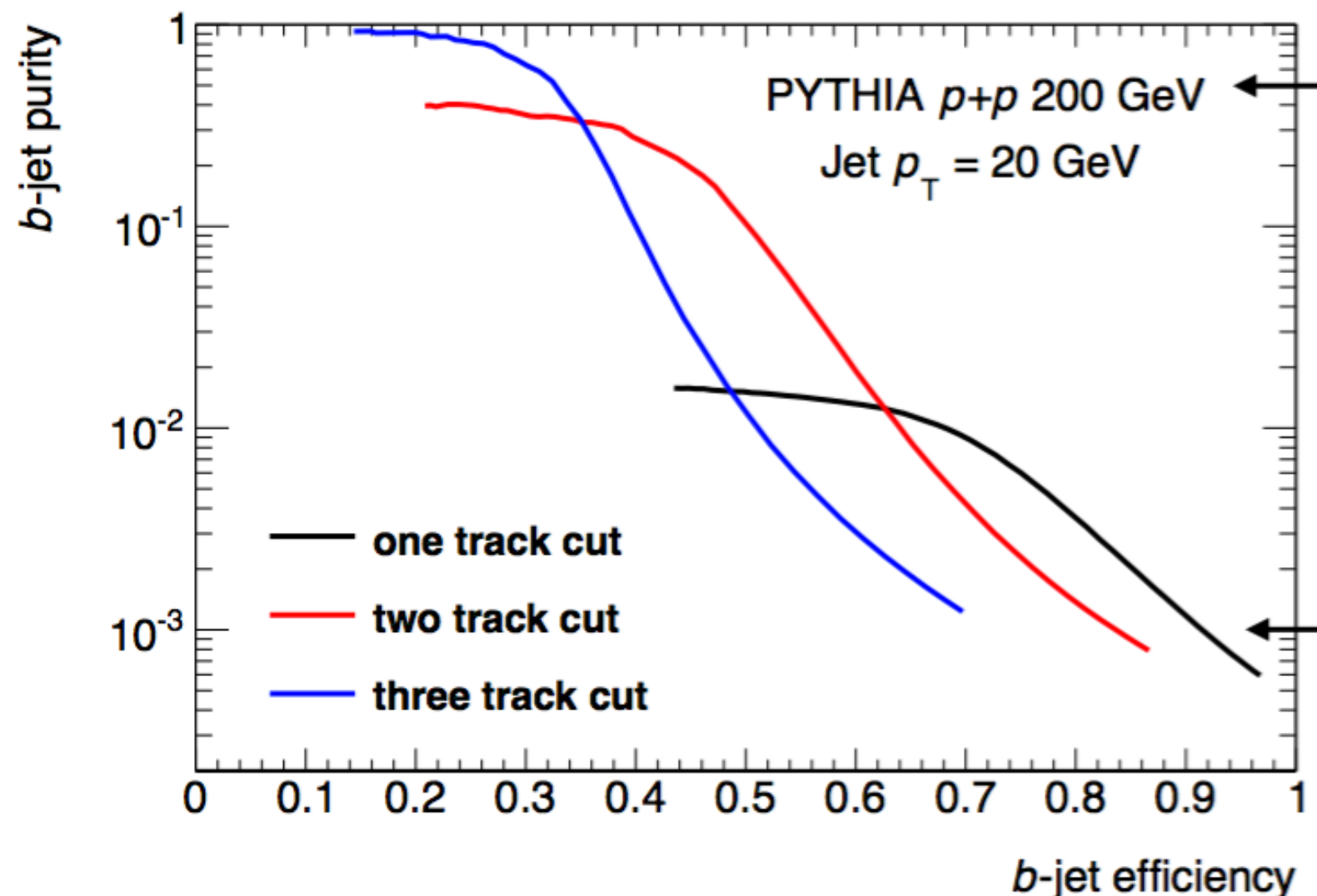
(1) **Short-term:** Calculate on the physics performance of various (defined) configurations for the ALD Charge

- (i) calculate basic tracking performance
- (ii) parameterize resolution & efficiency
- (iii) compute b-jet efficiency and purity (or rejection)



# Short Term Effort

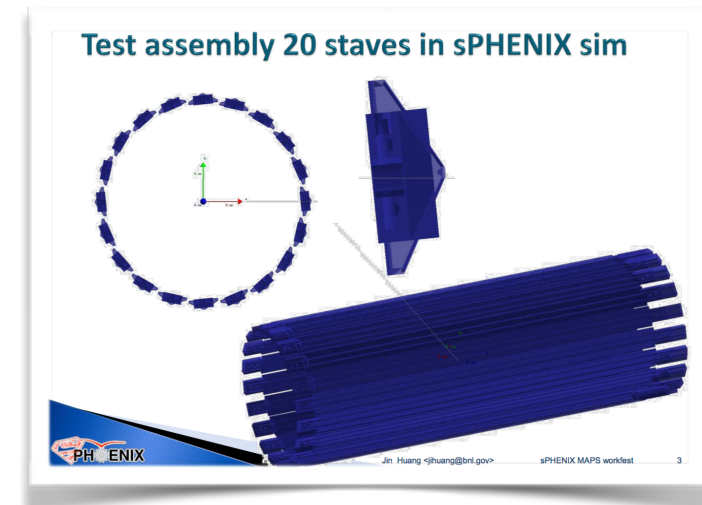
- (1) **Short-term:** Calculate on the physics performance of various (defined) configurations for the ALD Charge
- (i) calculate basic tracking performance
  - (ii) parameterize resolution & efficiency
  - (iii) compute b-jet efficiency and purity (or rejection)



# Longer Term Effort

## (2) **Longer-term:** Prepare for full-fledged detector simulations

(i) realistic stave/ladder geometries

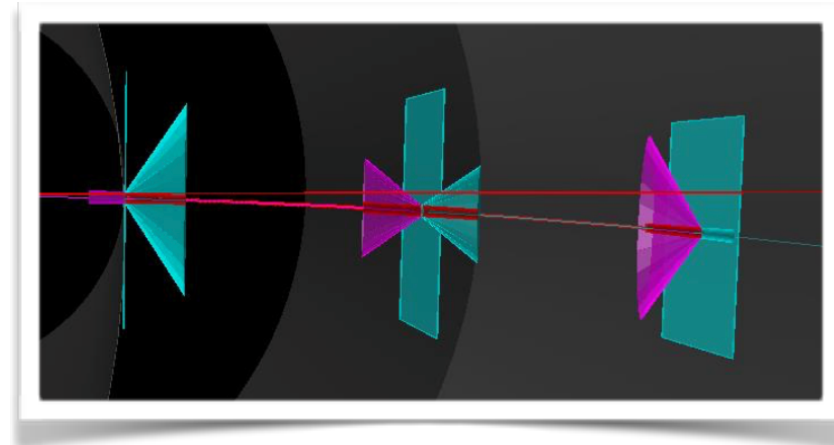


(ii) generic kalman tool

(a) fits with realistic geos (handle MS in cooling lines)

(b) split track merger (handle shingling)

(c) primary track fits (aka use the vertex)



(iii) multiple vertexing with RAVE tool

(a) secondary vertex b-jet identification

(b) multiple collisions vertexing



# Immediate Effort

## (3) Immediate-term: restore our simplified detector simulation capabilities

What I've tried:

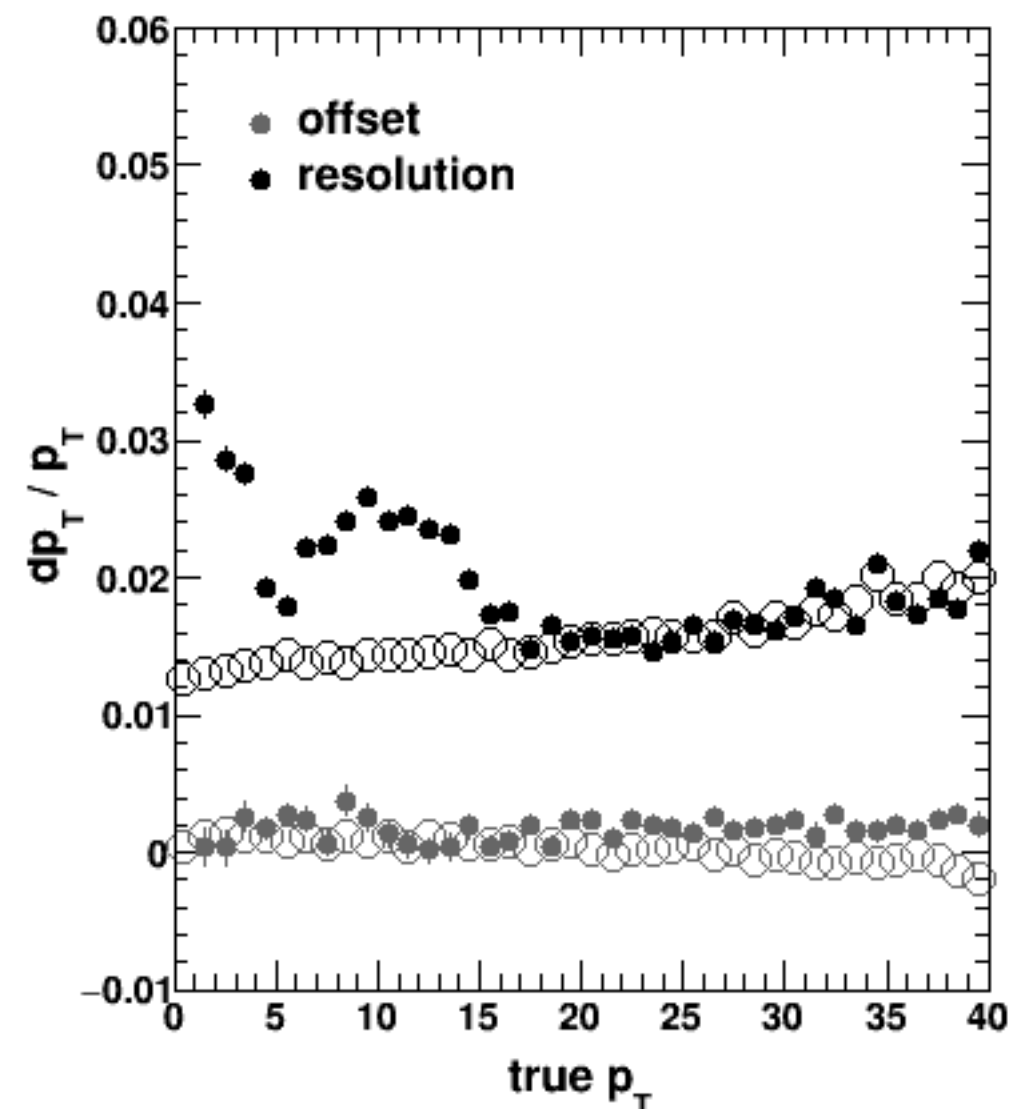
+ I assumed problem was in HelixHough or g4simulations or the macros

So I rewound these modules all the way back to mid-April, to get back to the April code base I had to “undo” Chris's linking of the GEANT4 & CLHEP libraries

Problem remained all the way back as far as I could go.

So I tried rebuilding my last branch submit and the problem was in it too... so I know my attempt at replication was missing the actual problem

Bad resolution, 7 layers of MAPS, new build



# Immediate Effort

## (3) Immediate-term: restore our simplified detector simulation capabilities

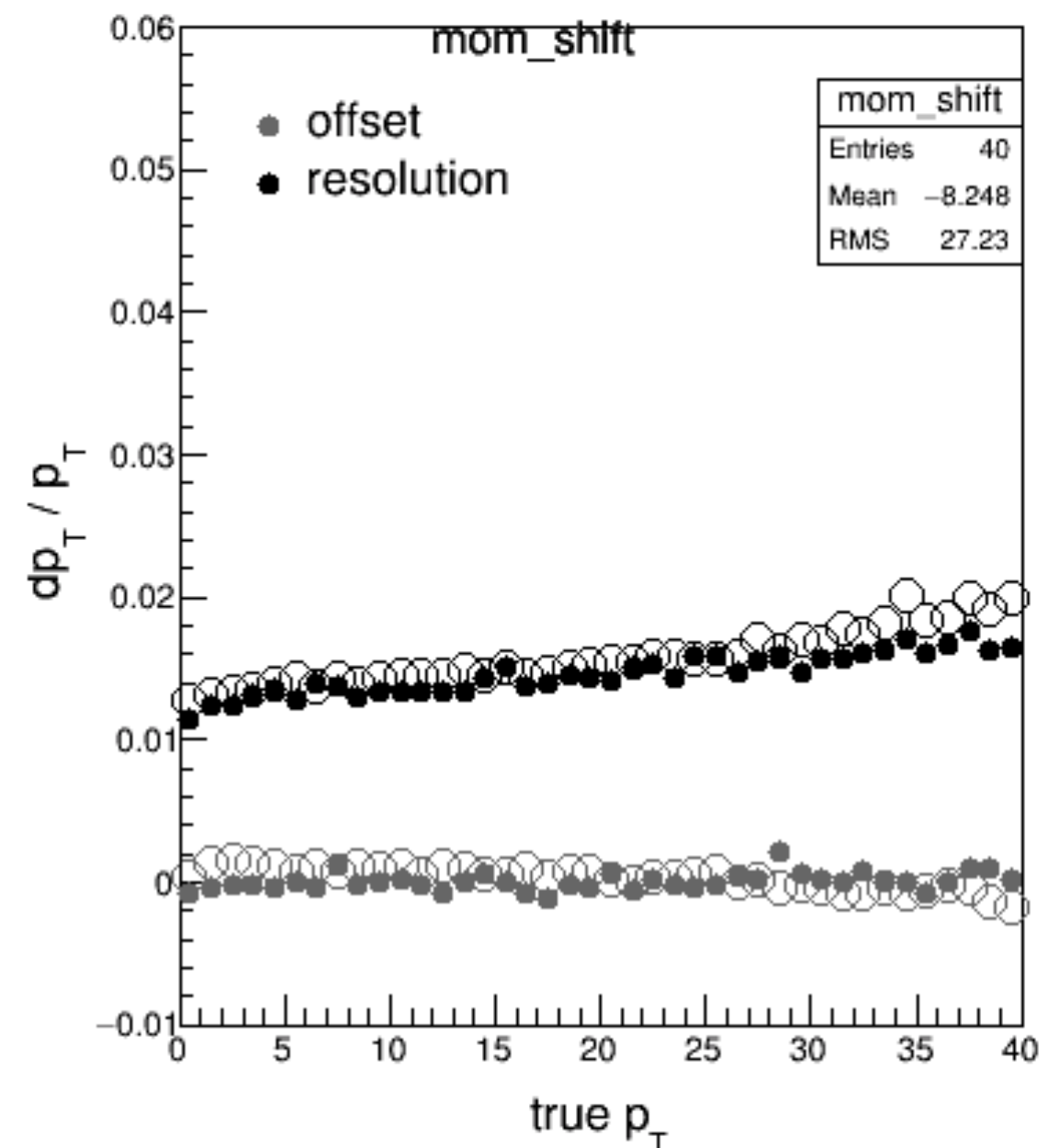
Good resolution, 7 layers of MAPS, tutorial VM

So I started with my tutorial VM from 4/7.

The code there worked fine. So I fast forward the tracking to the latest submits (minus one commit for the new G4 version).

The problem never reappeared.

So not the tracking software directly...



# Immediate Effort

## (3) Immediate-term: restore our simplified detector simulation capabilities

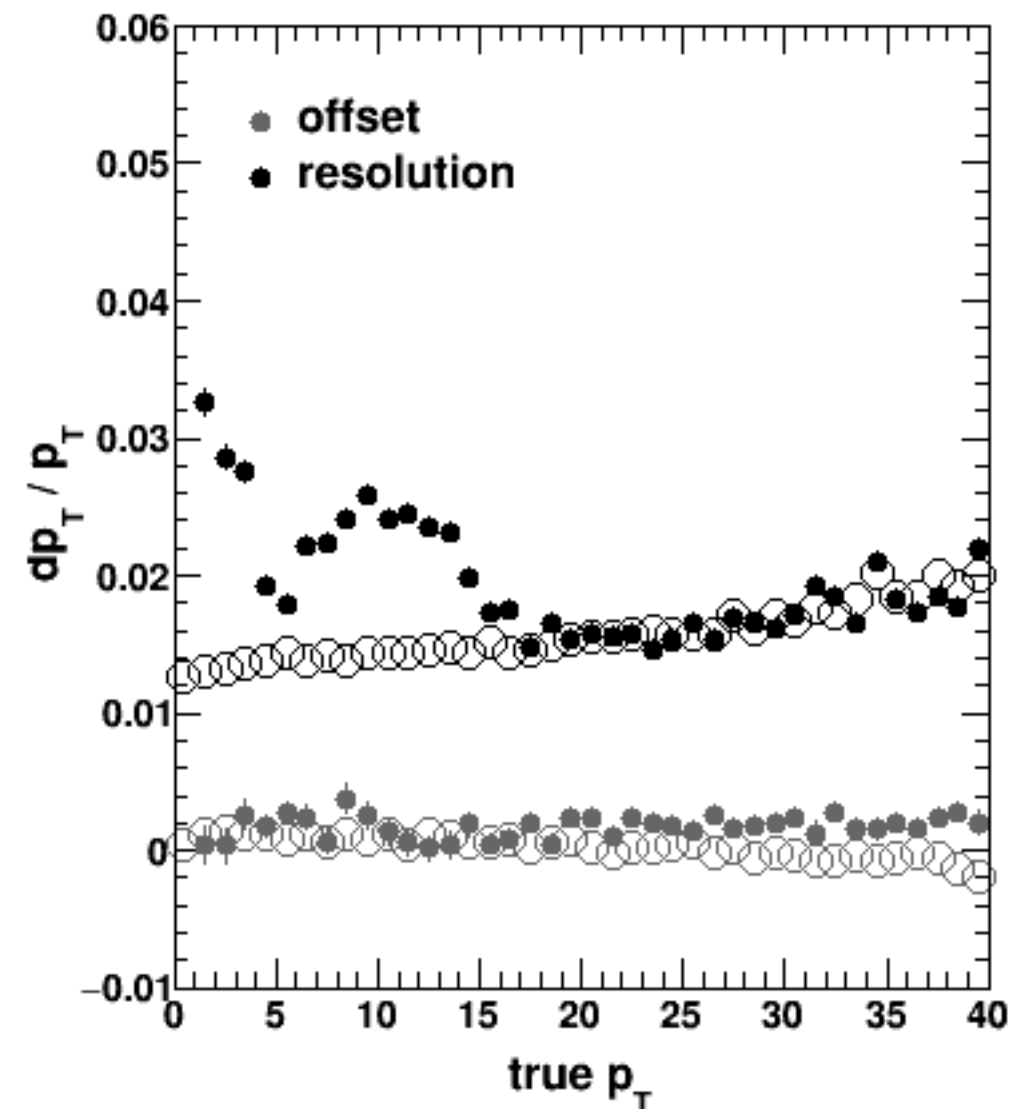
By now I was starting to doubt my working assumption... the problem is likely not under test

Asked CP to post a play build with the old G4 (still has new CLHEP FYI)

Recompiled against this build, and still have the problem.

Not directly the change in G4 versions

Bad resolution, 7 layers of MAPS, play build with old G4



# Immediate Effort

## (3) Immediate-term: restore our simplified detector simulation capabilities

Some ideas:

Is there a mix of CLHEP libraries in use causing problems?

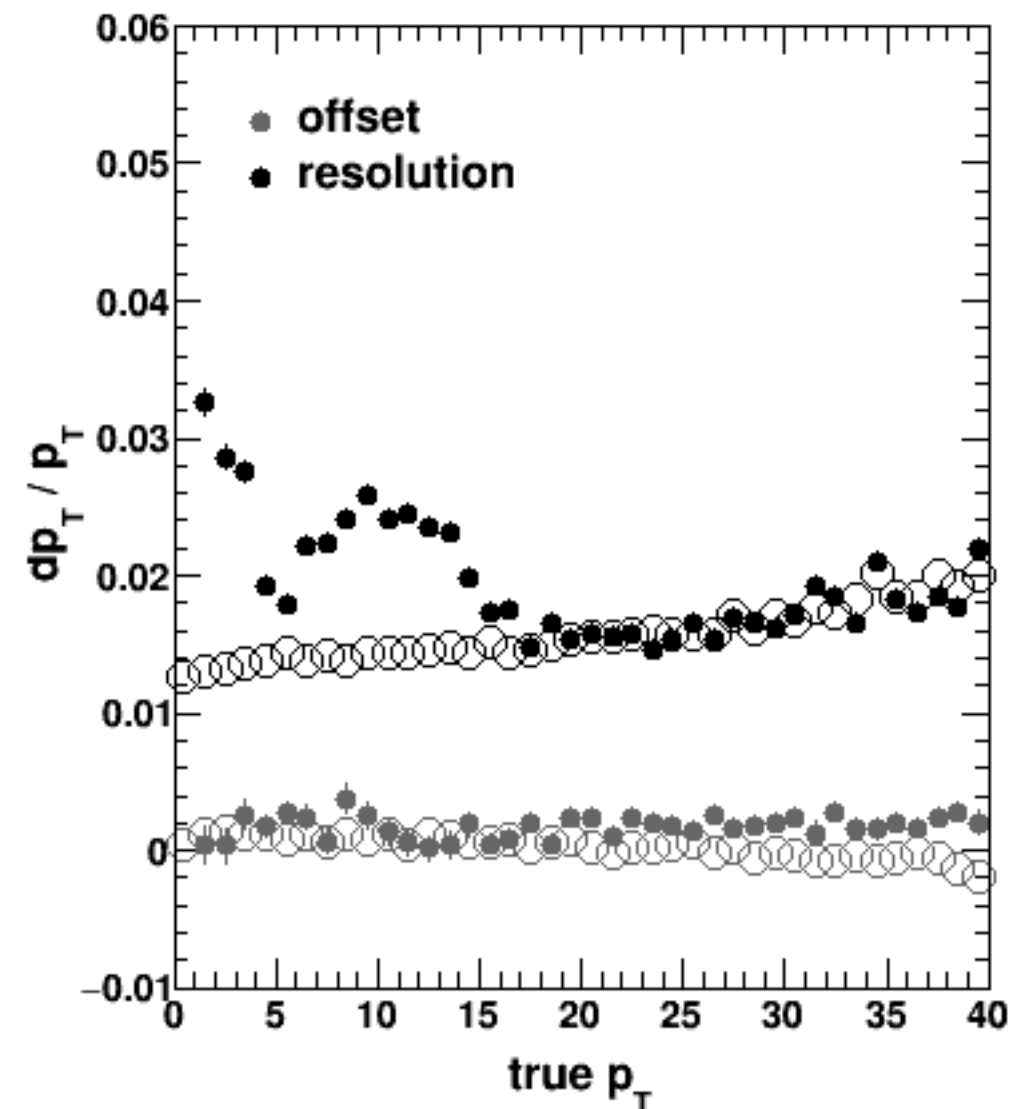
Can there be changes outside the tested modules? (I tried the latest fun4all build).

Can we try building a new play build against the old software base? (all old code)

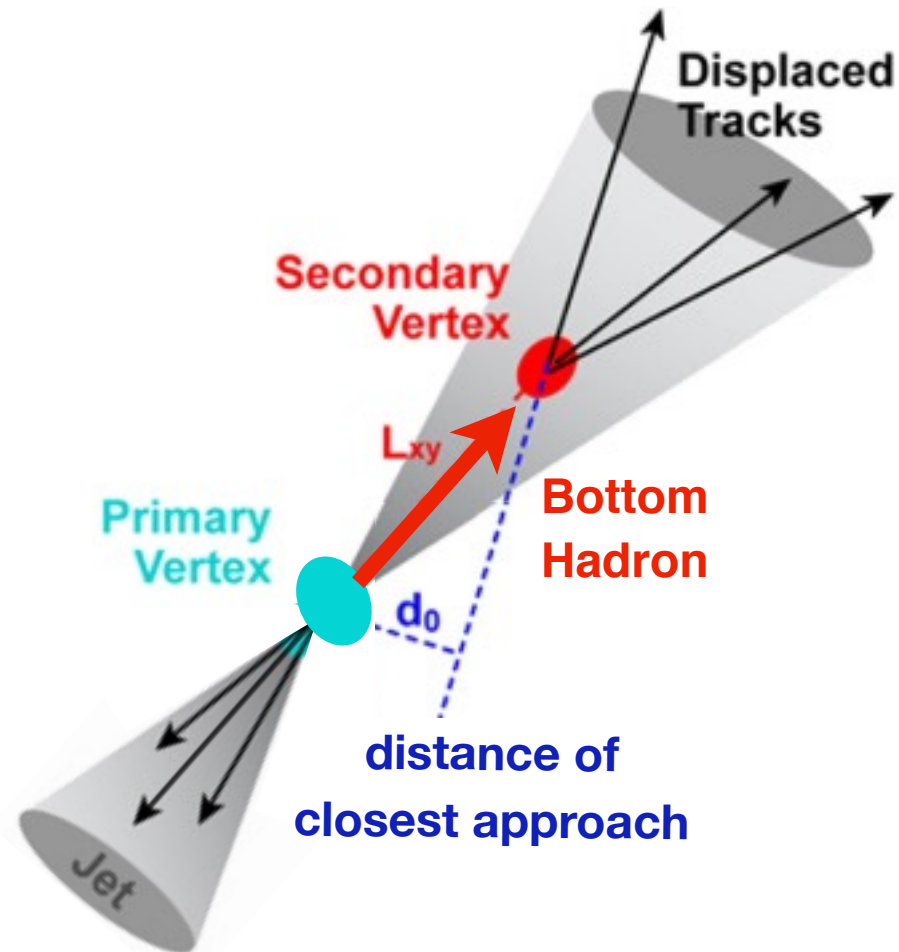
Shall I post the tutorial build and cshrc setup script to allow people at RCF to use a working build while we get this sorted??

I can now make momentum tests in ~5 mins (<2 hours)

Bad resolution, 7 layers of MAPS, play build with old G4



# Summary



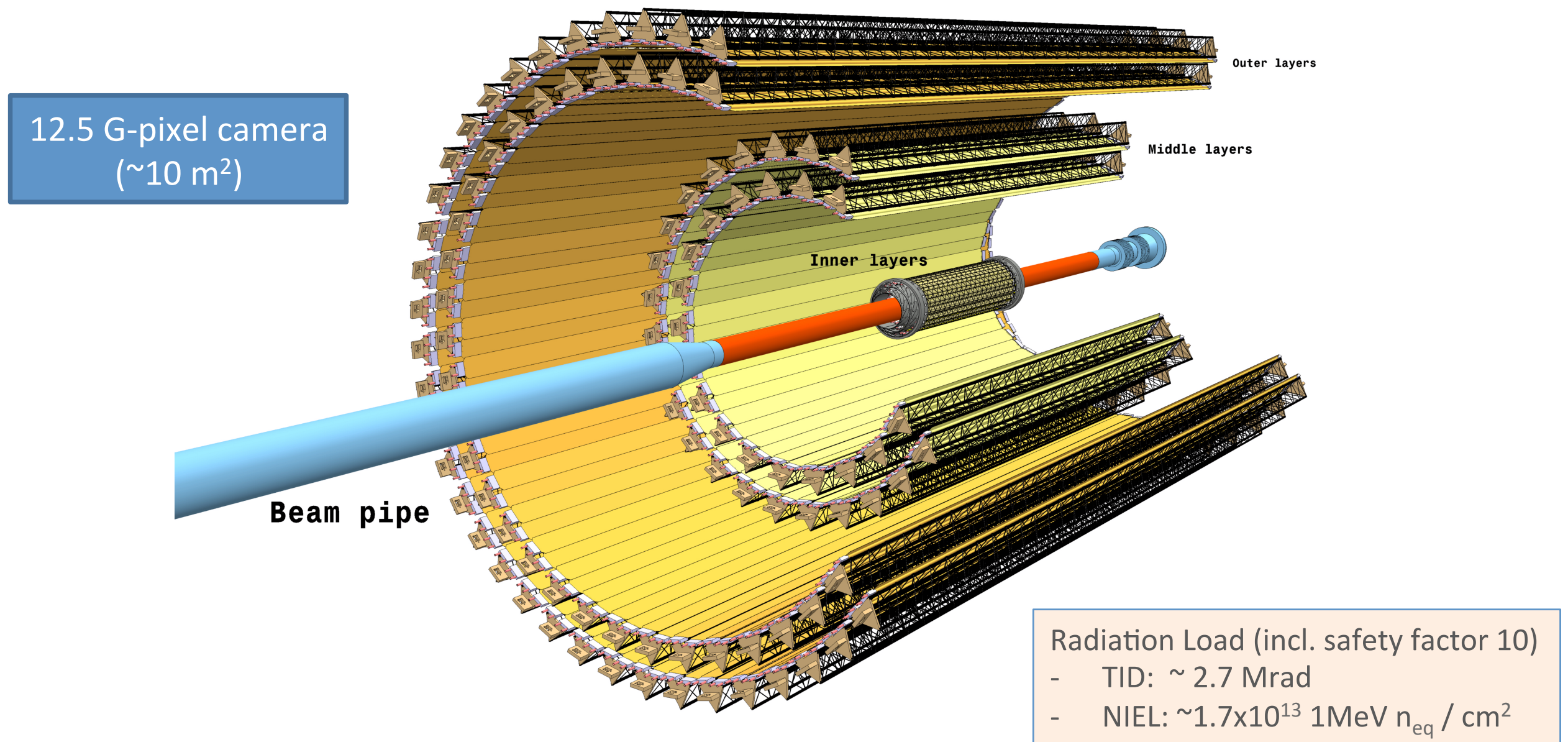
**Welcome new comers!** We will have a simulation tutorial session this afternoon after the task reports!

**Welcome experts!** Jin and I thank you for your attendance for these workshop days.

BACKUP SLIDES



# ALICE ITS Upgrade



## 7-layer barrel geometry based on CMOS Sensors

**r coverage:** 23 – 400 mm

**η coverage:**  $|\eta| \leq 1.22$

for tracks from 90% most luminous region

**3 Inner Barrel layers (IB)**

**4 Outer Barrel layers (OB)**

Material /layer : 0.3% X<sub>0</sub> (IB), 1% X<sub>0</sub> (OB)

## **Material thickness (1.3% per layer):**

More clear now that with the strip outer layers the material in the inner layers isn't a driver on the Upsilon separation, we should repeat that with the TPC option

Long term evolution will still replace the pixels

## **One-dimensional optimization in pitch (50um x 425um):**

VTX pixels were designed around a DCA-based analysis

Two track intersection probabilities needed for 2nd vertex reconstruction need to be understood

Can the VTX pixels perform the 2nd vertex reconstruction at all?

## **DAQ Rate:**

VTX pixel test saw 14 kHz at 60% live time, somewhat under our 15 kHz ~90% live time readout spec

New hardware could design in the full readout bandwidth

Not sure where the next bottleneck would be, more than a small gain?

## **Limited TPC integration flexibility:**

A finite surface area of VTX pixels is available, we can cover 2.5 cm and 3.6 cm, **no spares**

TPC based tracking starts no closer than 30 cm

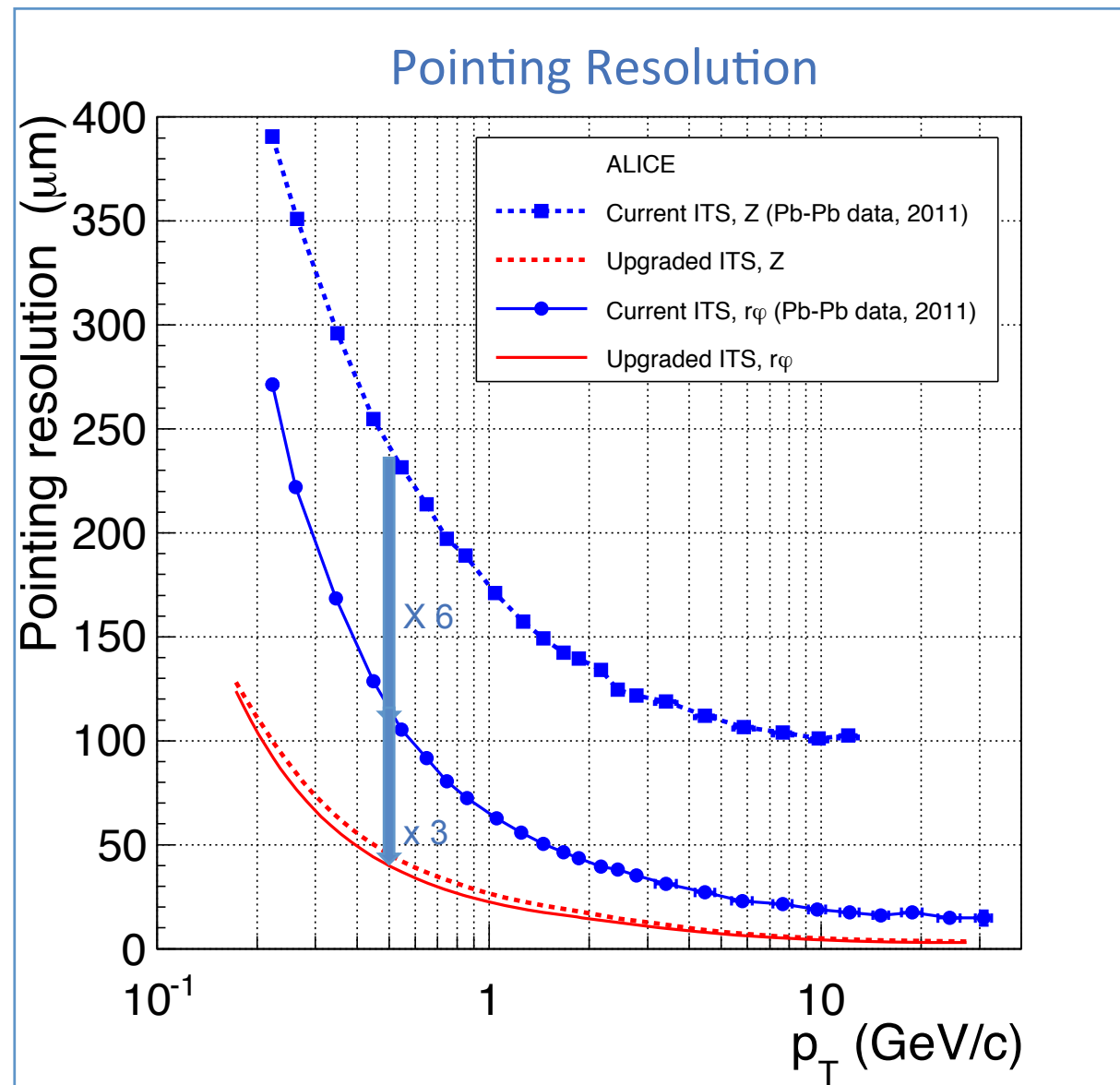
3.6 cm to 30 cm is a long jump to make

We may need a tracking layer between 4.4 and 30 cm to break ambiguities in the tracking

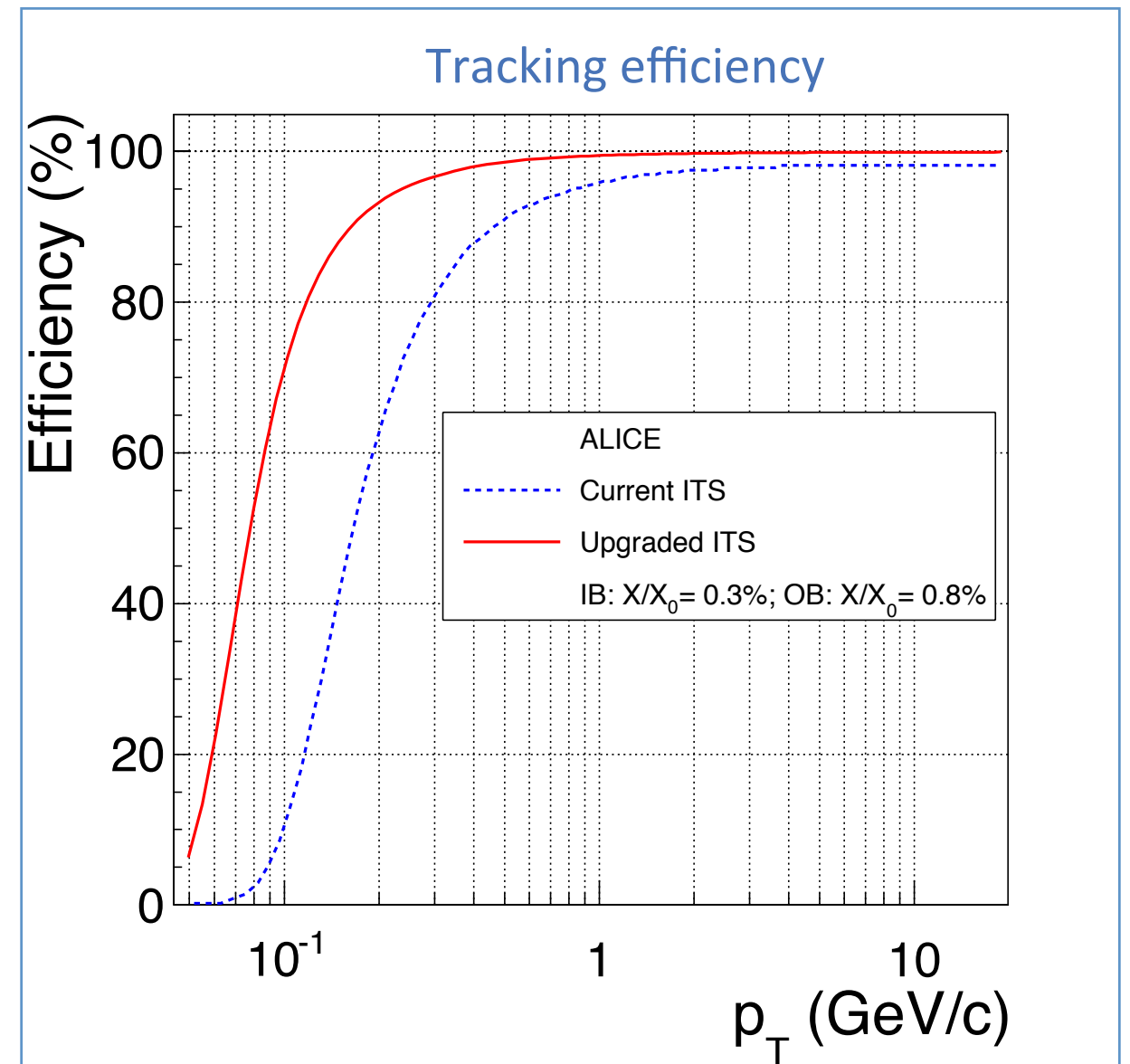


# ITS Motivation

## Impact parameter resolution



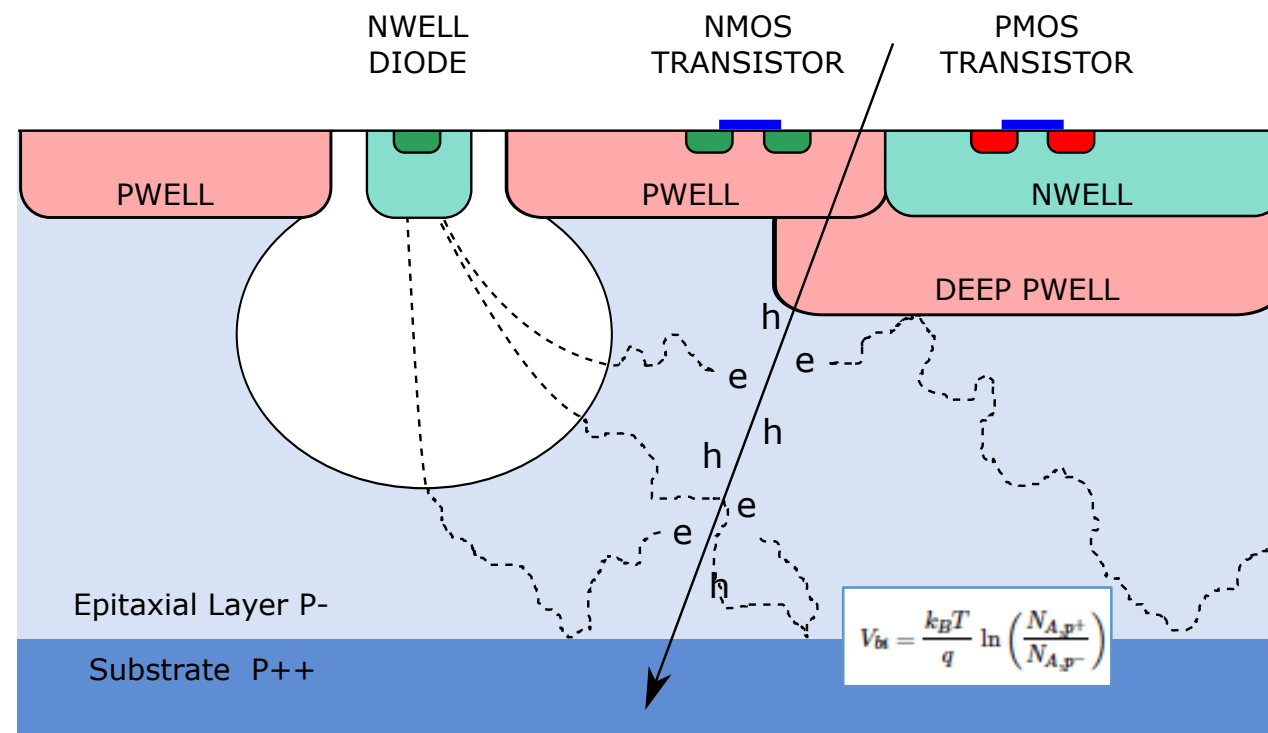
## Tracking efficiency (ITS standalone)



$\sim 40 \mu\text{m}$  at  $p_T = 500 \text{ MeV/c}$

# ALPIDE pixel technology

## CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



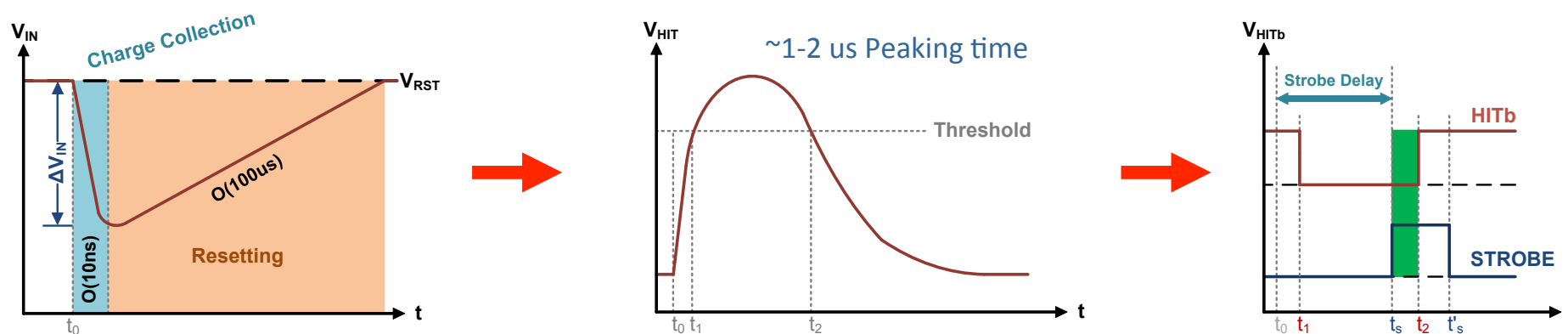
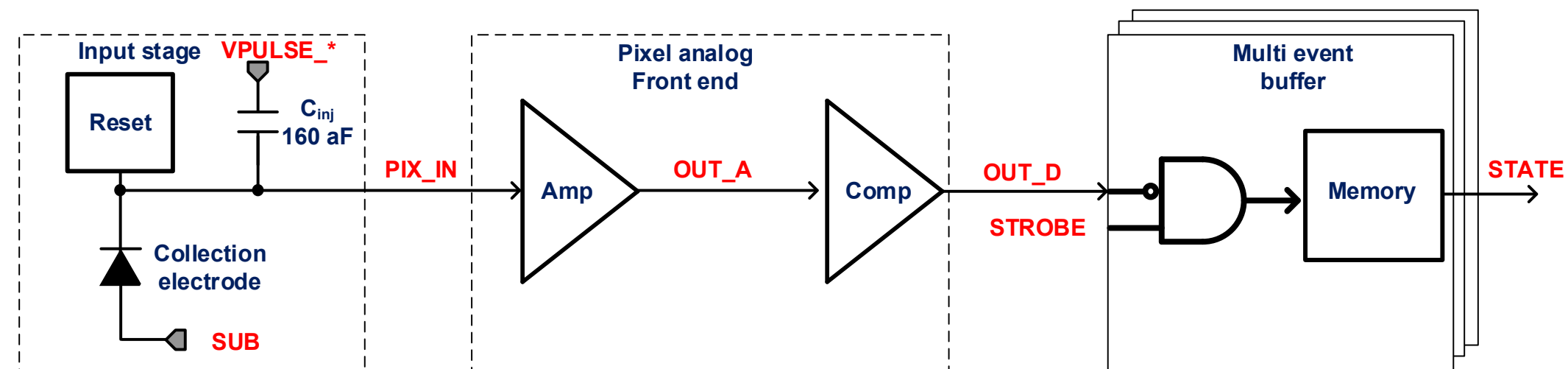
### Tower Jazz 0.18 μm CMOS

- feature size 180 nm
- metal layers 6
- gate oxide 3nm

substrate:  $N_A \sim 10^{18}$   
 epitaxial layer:  $N_A \sim 10^{13}$   
 deep p-well:  $N_A \sim 10^{16}$

- ▶ High-resistivity ( $> 1\text{k}\Omega\text{ cm}$ ) p-type epitaxial layer (18μm to 30μm) on p-type substrate
- ▶ Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance
- ▶ Application of (moderate) reverse bias voltage to substrate (contact from the top) can be used to increase depletion zone around NWELL collection diode
- ▶ Deep PWELL shields NWELL of PMOS transistors to allow for full CMOS circuitry within active area

# ALPIDE Operation

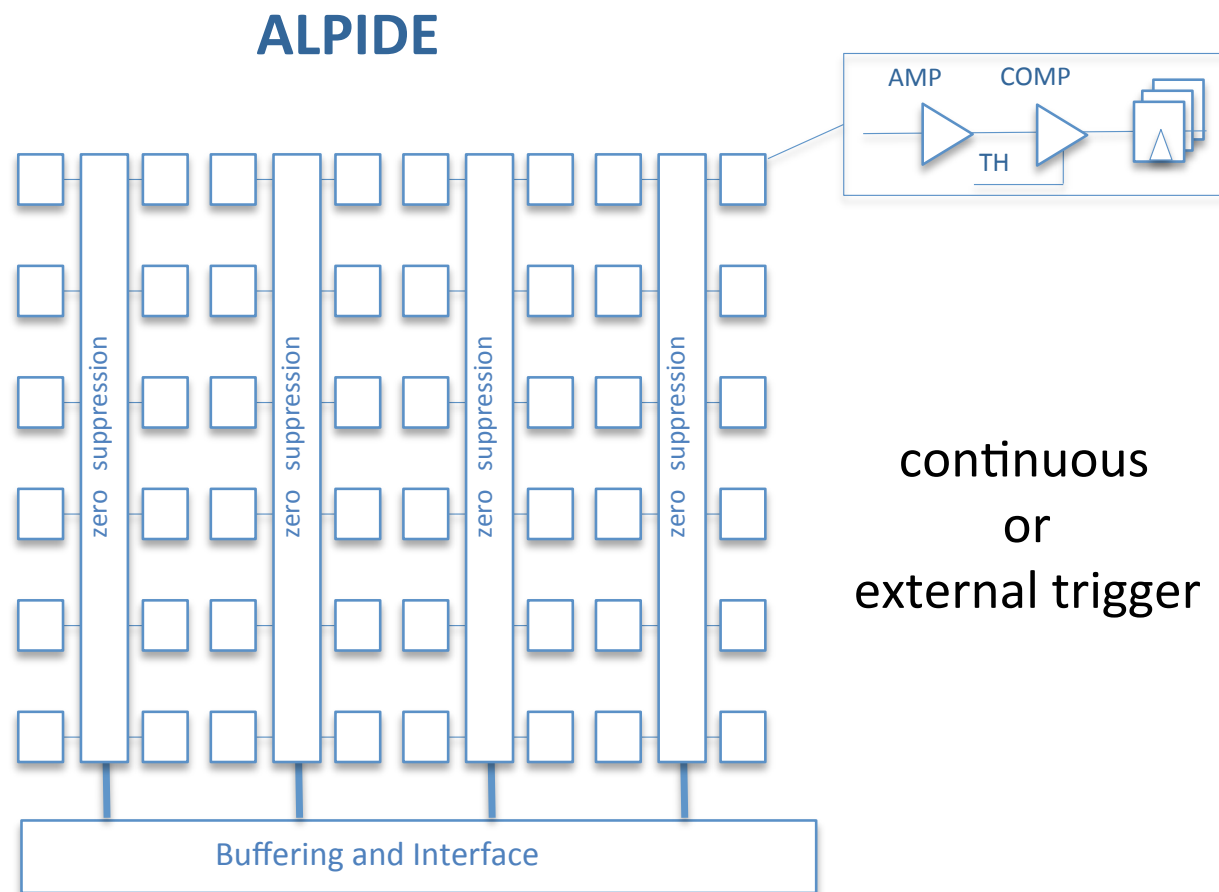


## Front-end acts as delay line

- Sensor and front-end continuously active
- Upon particle hit front-end forms a pulse with  $\sim 1\text{-}2\mu\text{s}$  peaking time
- Threshold is applied to form binary pulse
- Hit is latched into a (3-bit) memory if strobe is applied during binary pulse

ultra low-power front-end circuit  
40nW / pixel

# ALPIDE Readout



## Architecture

- ▶ In-pixel amplification
- ▶ In-pixel discrimination
- ▶ In-pixel (multi-) hit buffer
- ▶ In-matrix sparsification

## Key Features

- ⊙ 28  $\mu\text{m}$  x 28 mm pixel pitch
- ⊙ Continuously active, ultra-low power front-end (40nW/pixel)
- ⊙ No clock propagation to the matrix → ultra-low power matrix readout (2mW whole chip)
- ⊙ Global shutter (<10 $\mu\text{s}$ ): triggered acquisition or continuous

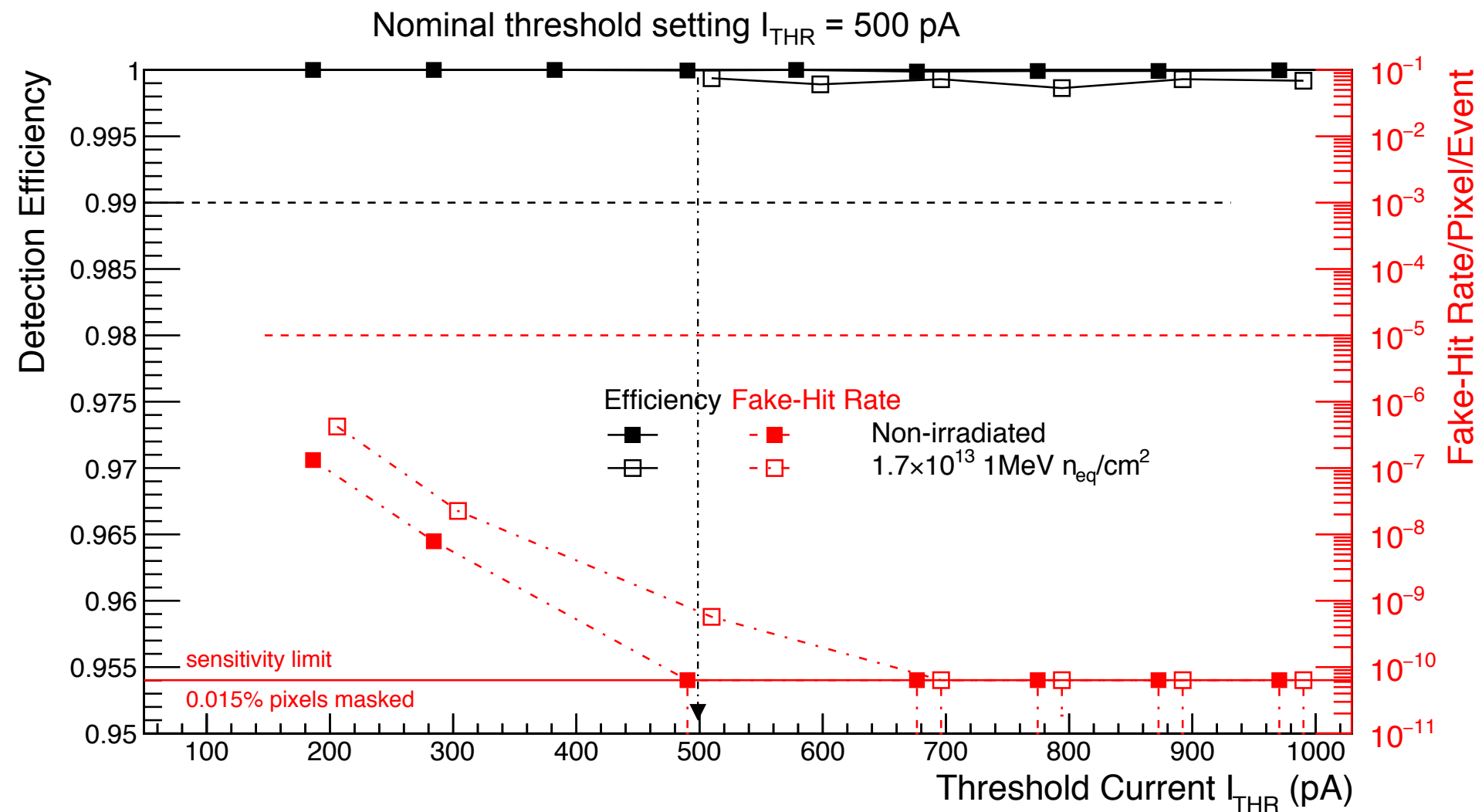




# ALICE Test Beam Data

## Efficiency and fake hit rate

epi=30 $\mu$ m,  $V_{BB}$ =-6V, spacing=4 $\mu$ m



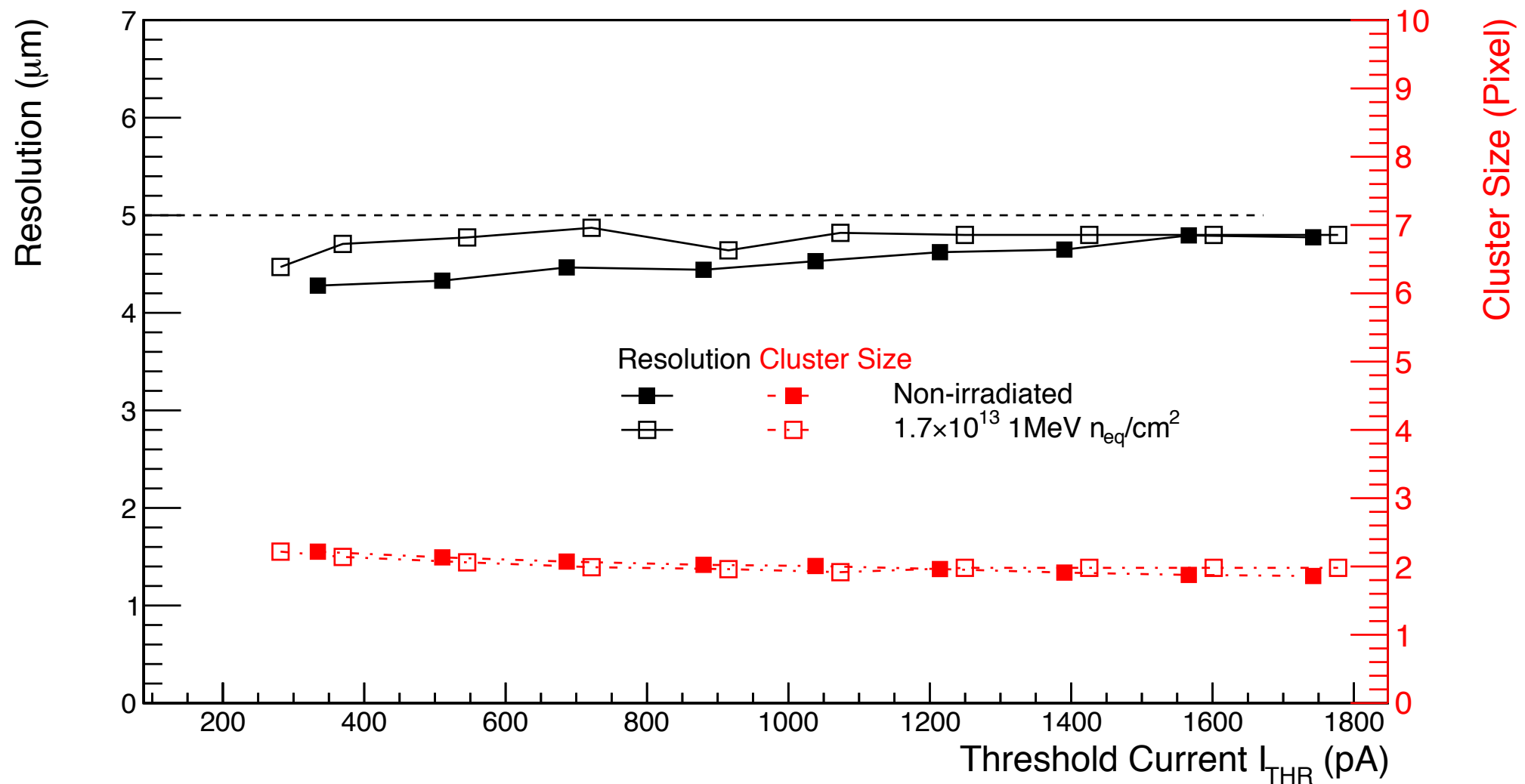
Even larger operation margin for 30 $\mu$ m epi layer and 4 $\mu$ m spacing

- Results refer to chips with 30 $\mu$ m high-res epi layer, thinned to 50  $\mu$ m:  
1 non irradiated and 1 irradiated with  $10^{13}$  1MeV  $n_{eq} / cm^2$

# ALICE Test Beam Data #2

## Spatial Resolution and Cluster Size

epi=30 $\mu$ m,  $V_{BB}$ =-6V, spacing=4 $\mu$ m

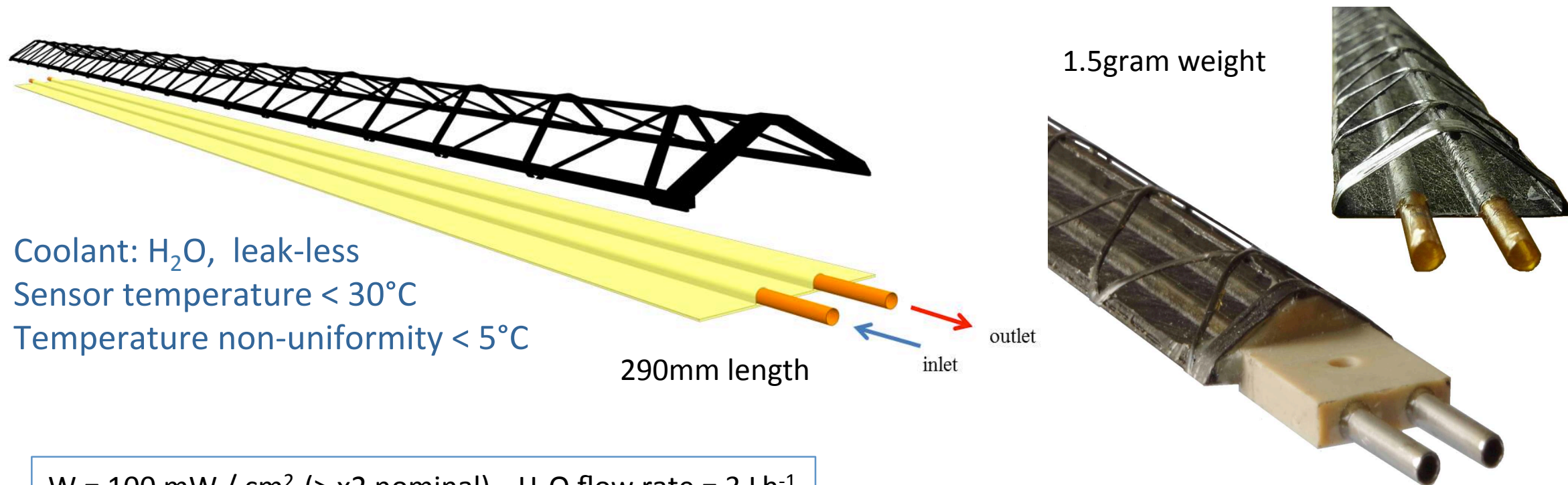


$\sigma_{det} \approx 5 \mu\text{m}$  is achieved before and after irradiation

- Results refer to chips with 30 $\mu$ m high-res epi layer, thinned to 50  $\mu$ m
- 1 non irradiated and 1 irradiated with  $1.7 \times 10^{13}$  1MeV  $n_{eq} / \text{cm}^2$

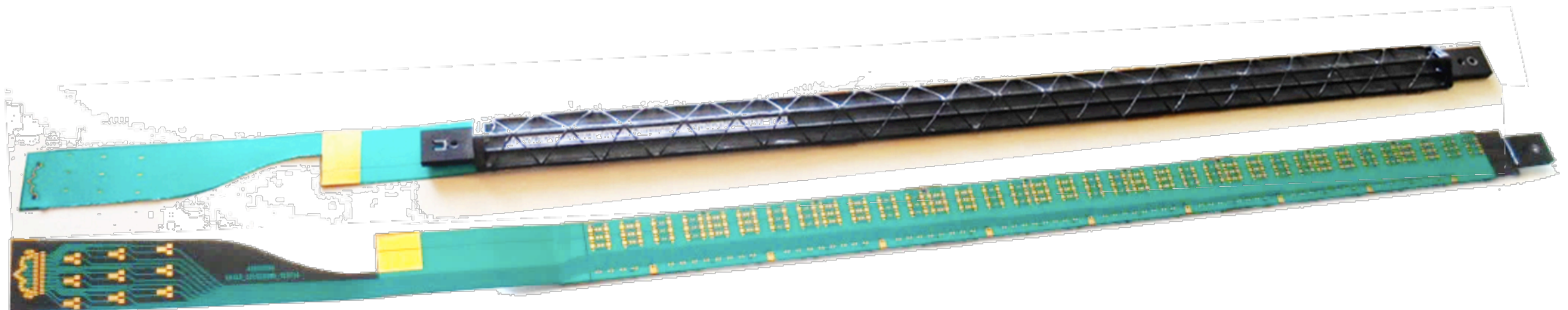
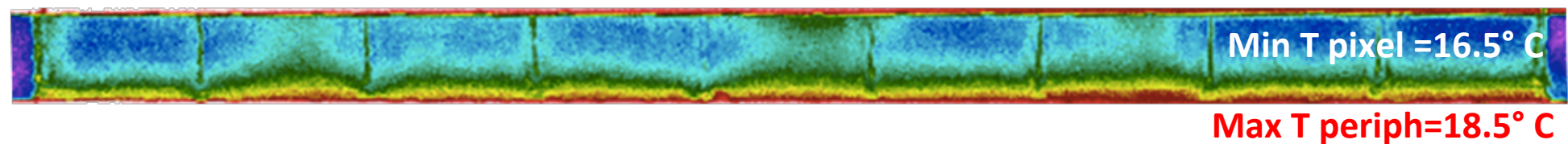


# Inner Barrel Staves



$W = 100 \text{ mW} / \text{cm}^2$  ( $> \times 2$  nominal),  $\text{H}_2\text{O}$  flow rate =  $3 \text{ Lh}^{-1}$

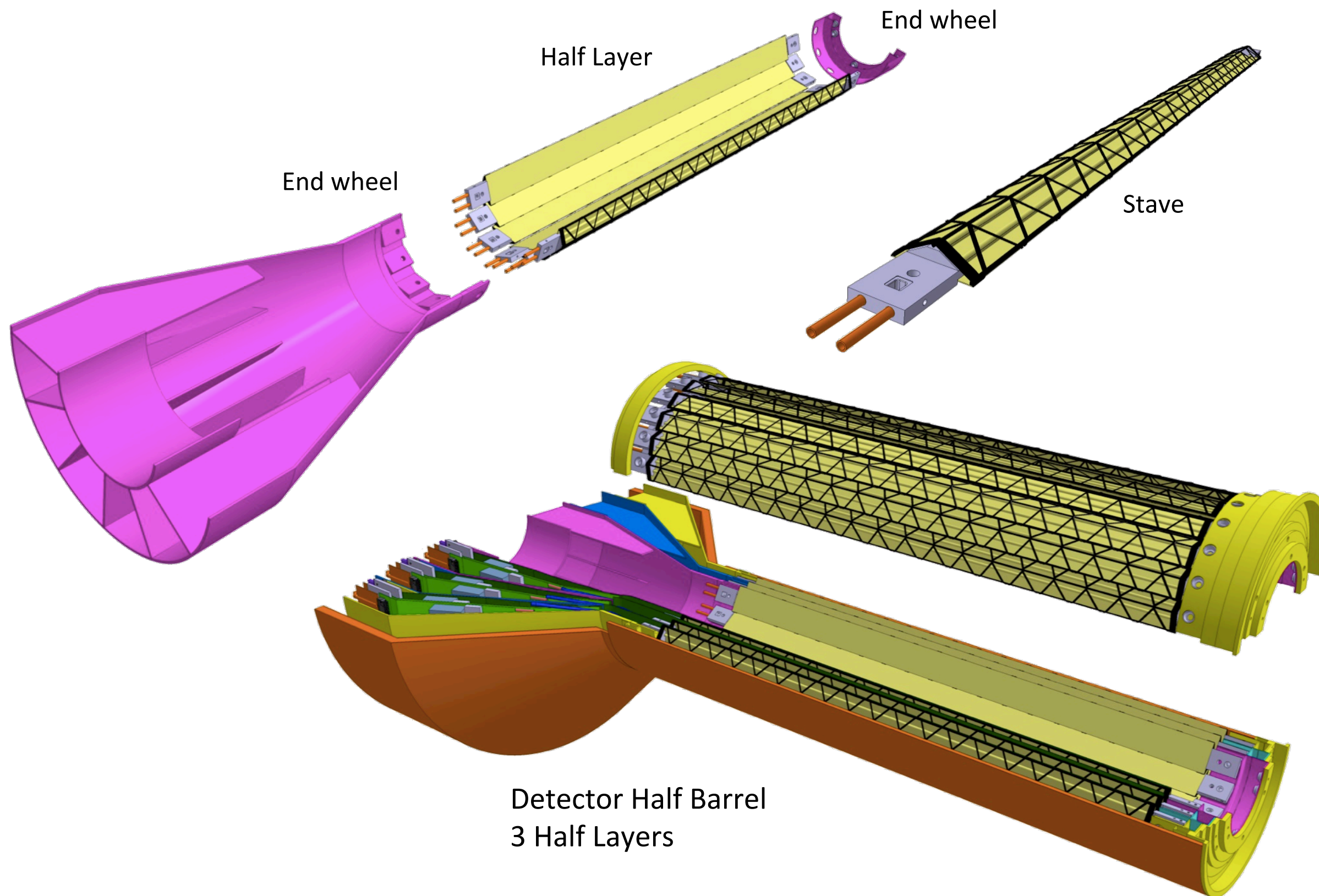
$T_{\text{in}} = 15.8^\circ\text{C}$   
 $T_{\text{out}} = 16.6^\circ\text{C}$





# ALICE Inner Barrel Support & Services

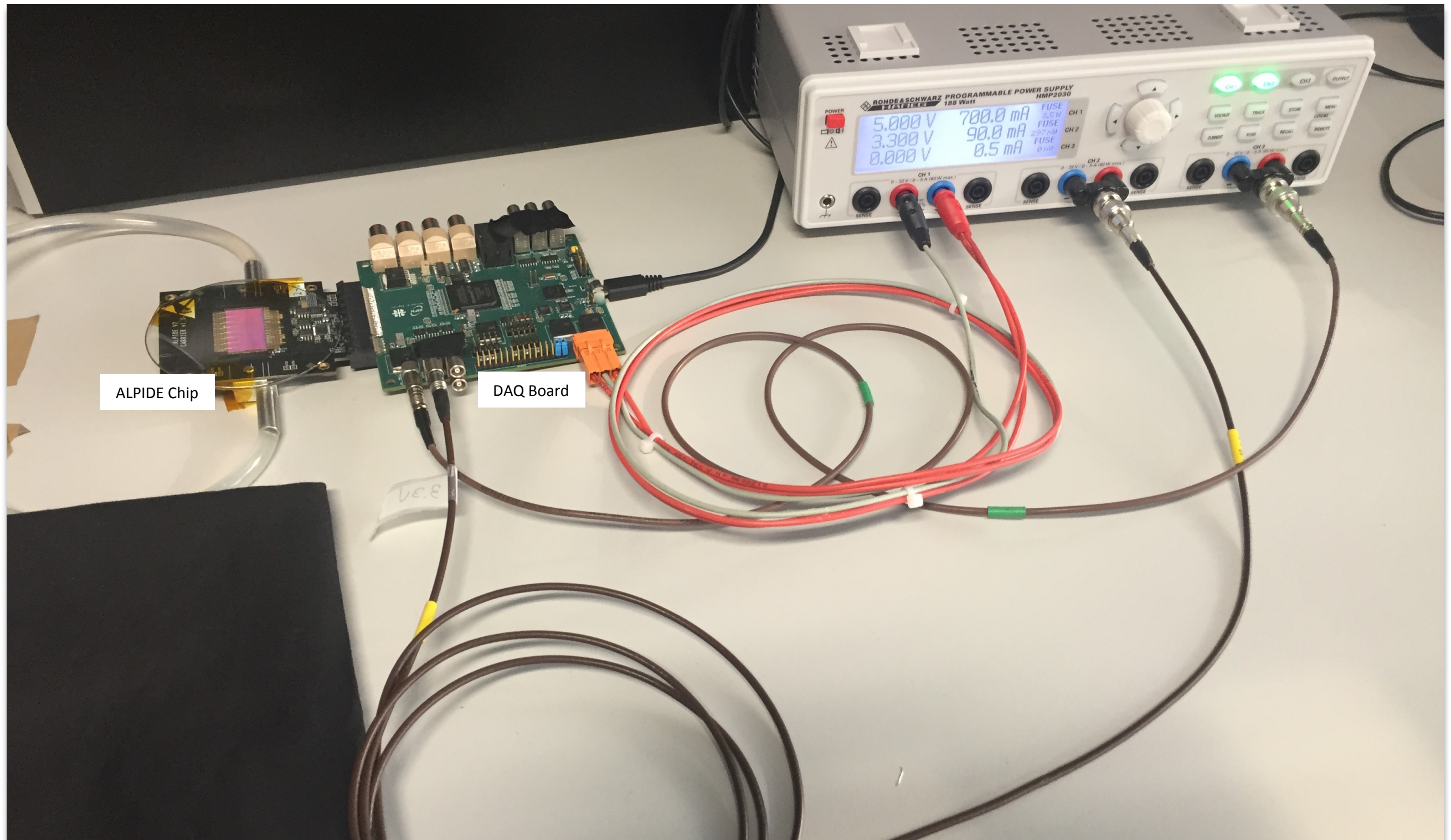
35





# Detector Prototyping

36





# Detector Prototyping

Readout Unit Prototype Version 0a ("RUv0a")

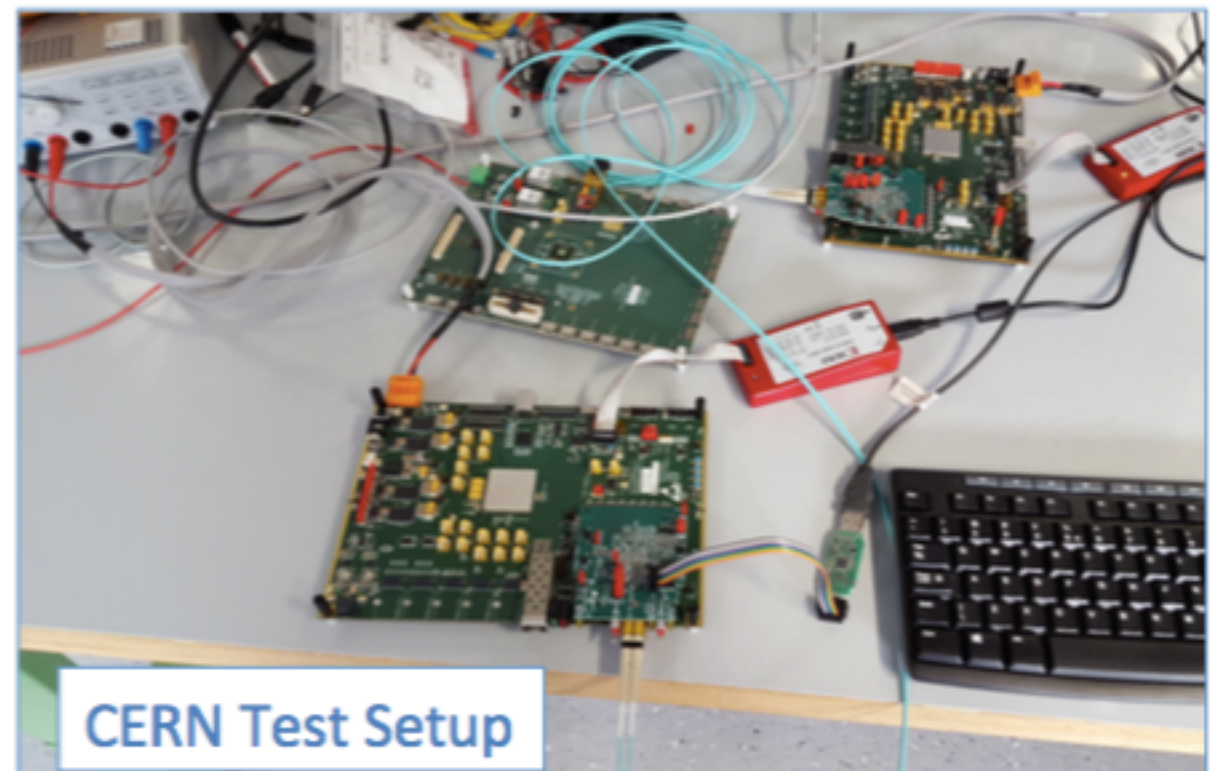


GBT FMC Mezzanine ("GBTxFMC")  
Readout Unit Daughter Board

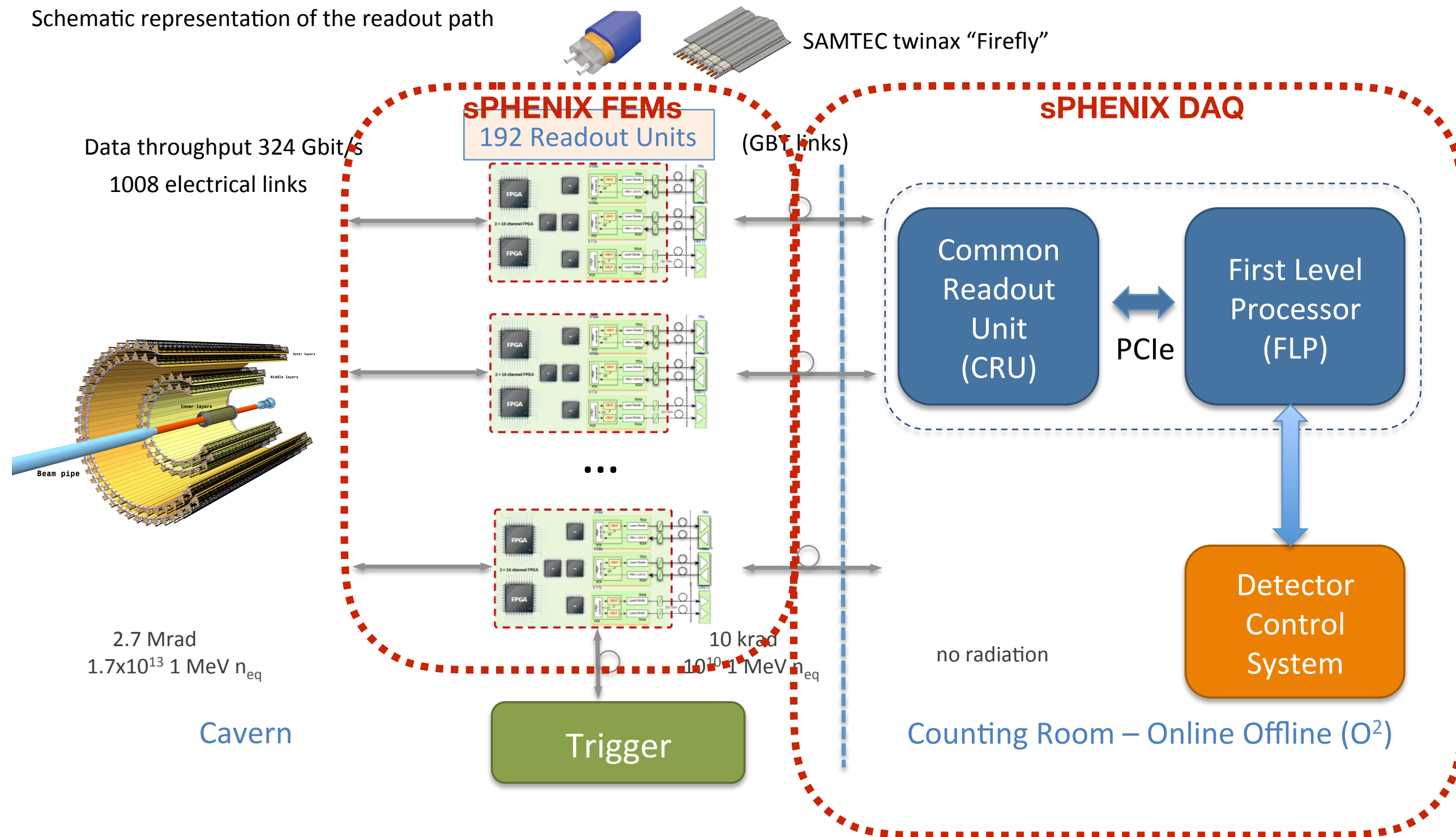
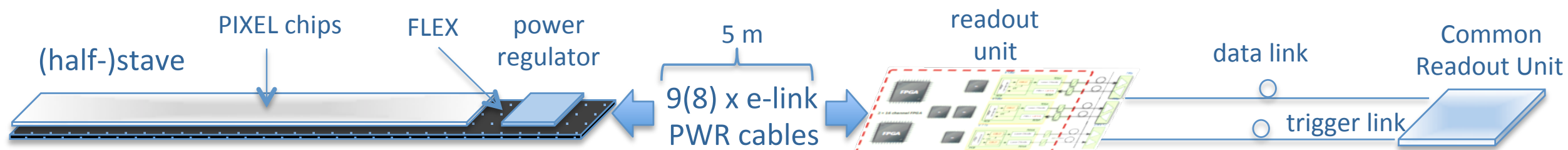


First Functional Prototype of  
Readout Electronics is available

- All interfaces are working
- Firmware development has started



# Readout Scheme





# LANL LDRD Deliverables

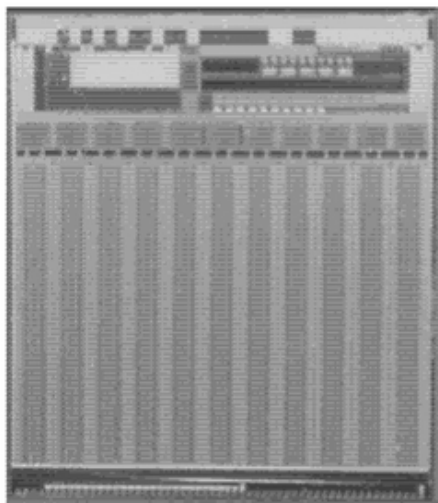
Our primary experimental goal for the LDRD process is a small-coverage 3-layer prototype tracker with MAPS-based sensor arrays.

Purpose: garner experience with MAPS, finalize the technical design and readout electronics for sPHENIX.

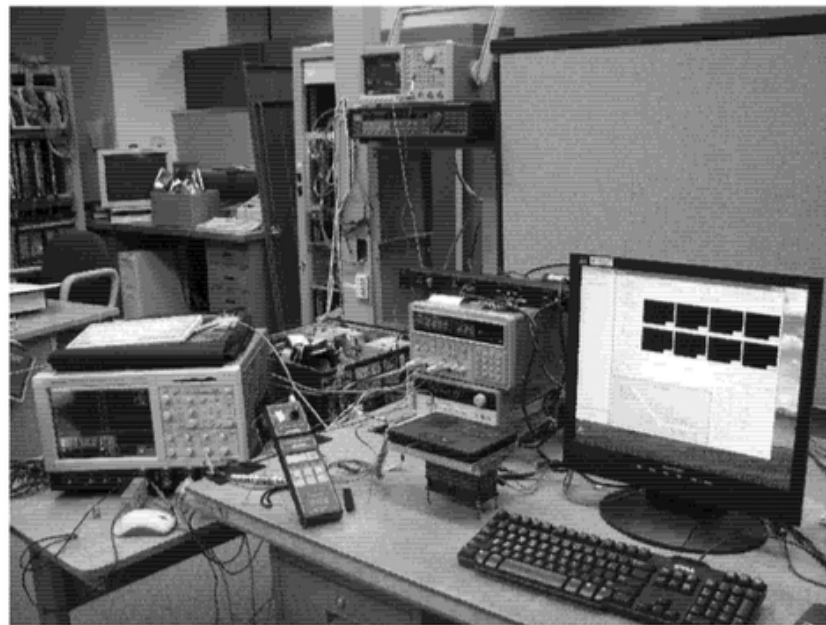


Prepare fully for final construction activities.

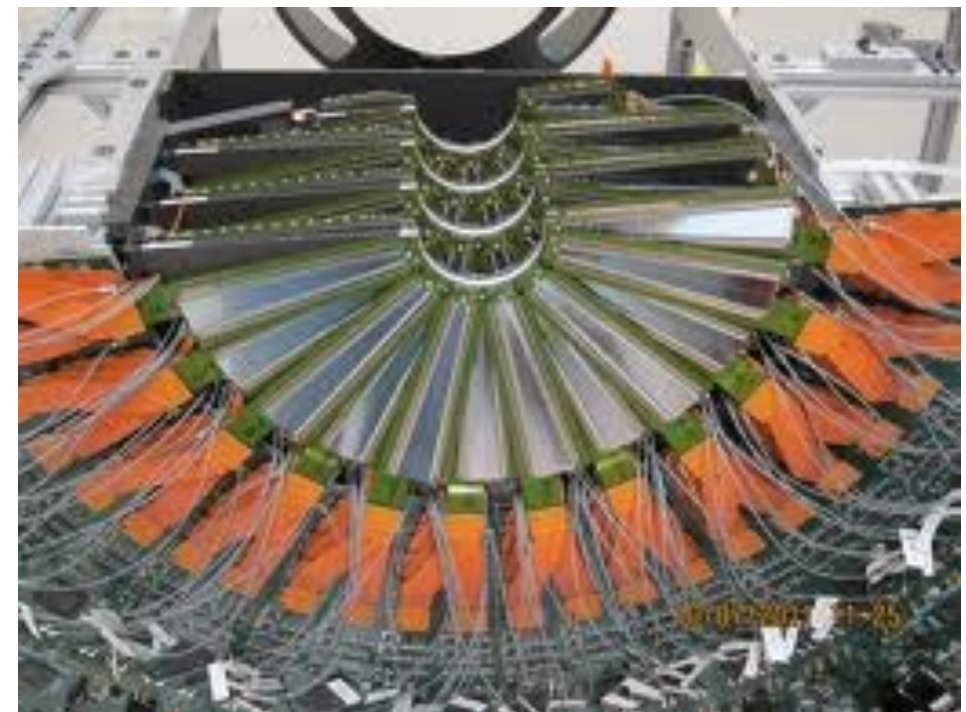
prototyping under LDRD:



prototype pixel sensor



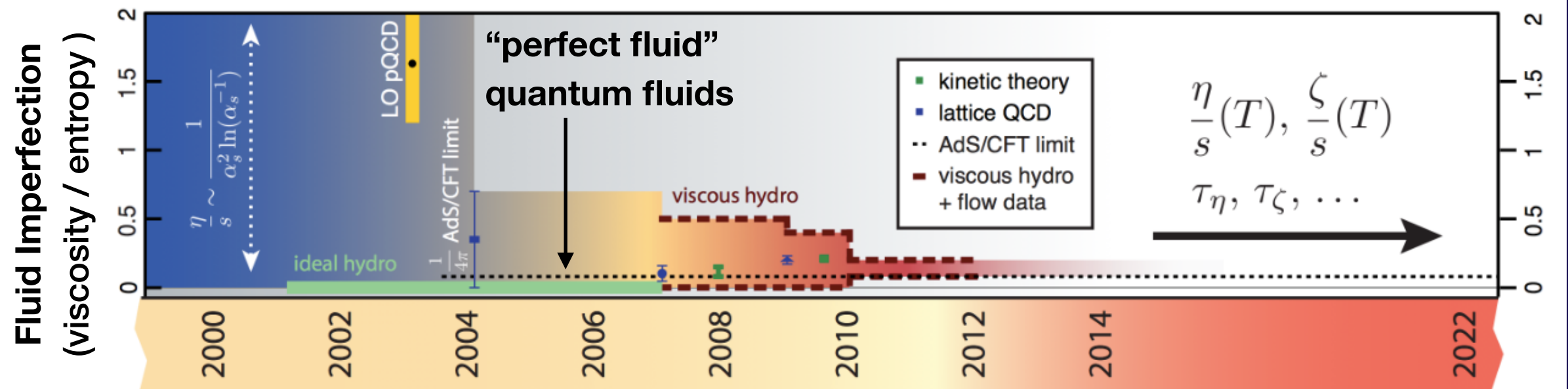
final tracker support after LDRD:



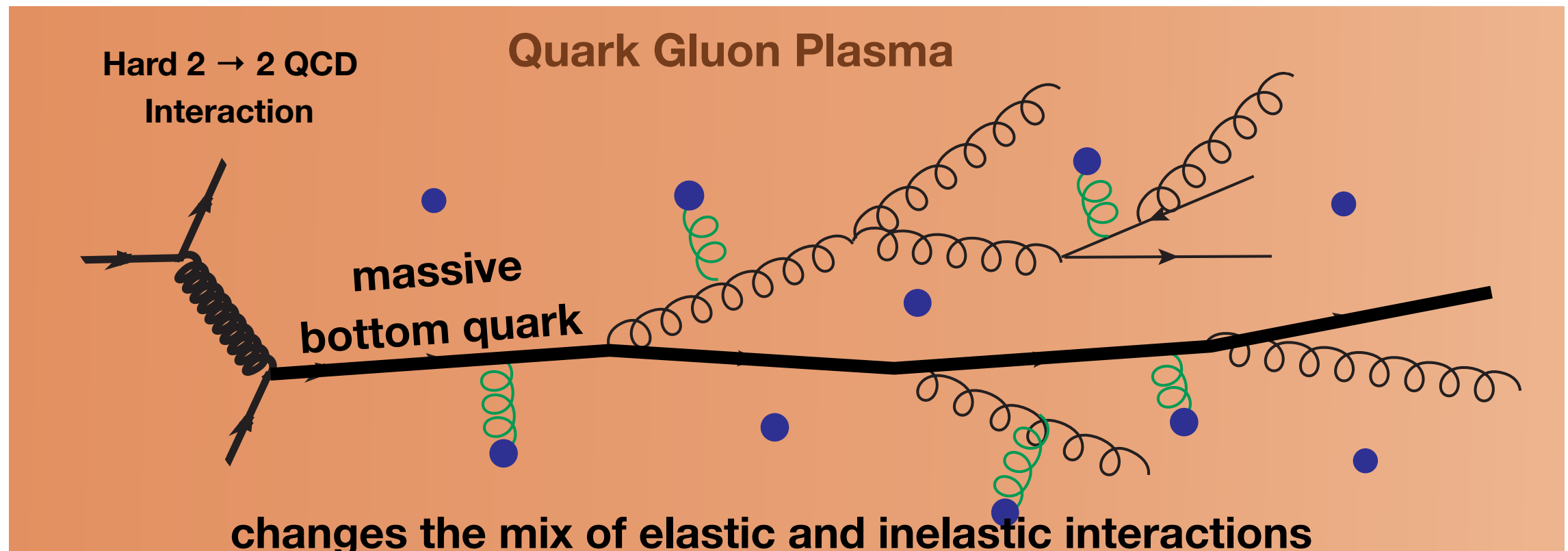
this is a proven successful strategy

**Our proposal was well received and we were invited to expand the scope and resubmit. We were also highly ranked in this years annual LDRD priorities.**

## Macroscopic Picture of the Quark Gluon Plasma



## Microscopic Picture of the Quark Gluon Plasma ??





# Interconnection of pixel chip to flex PCB

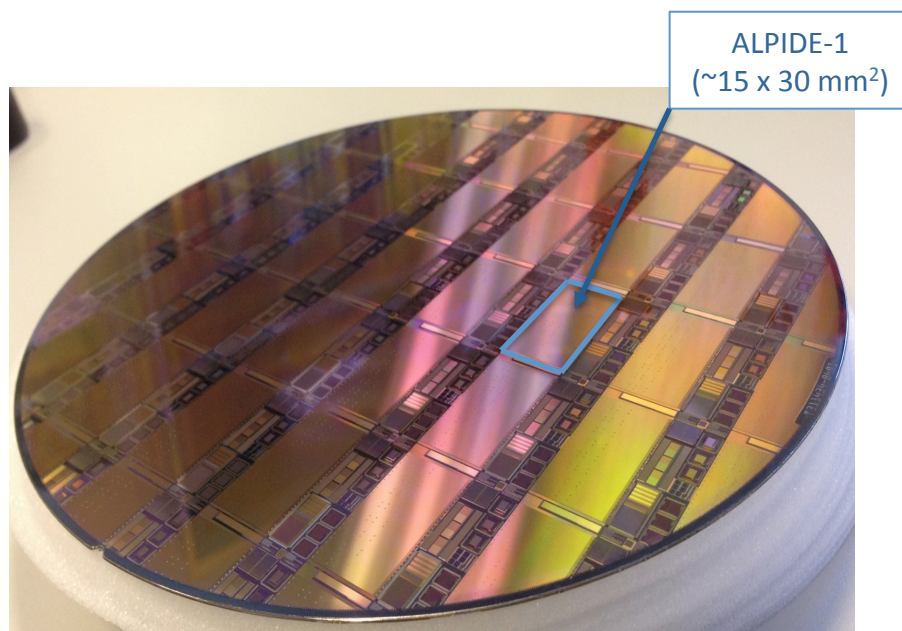
A Large Ion Collider Experiment



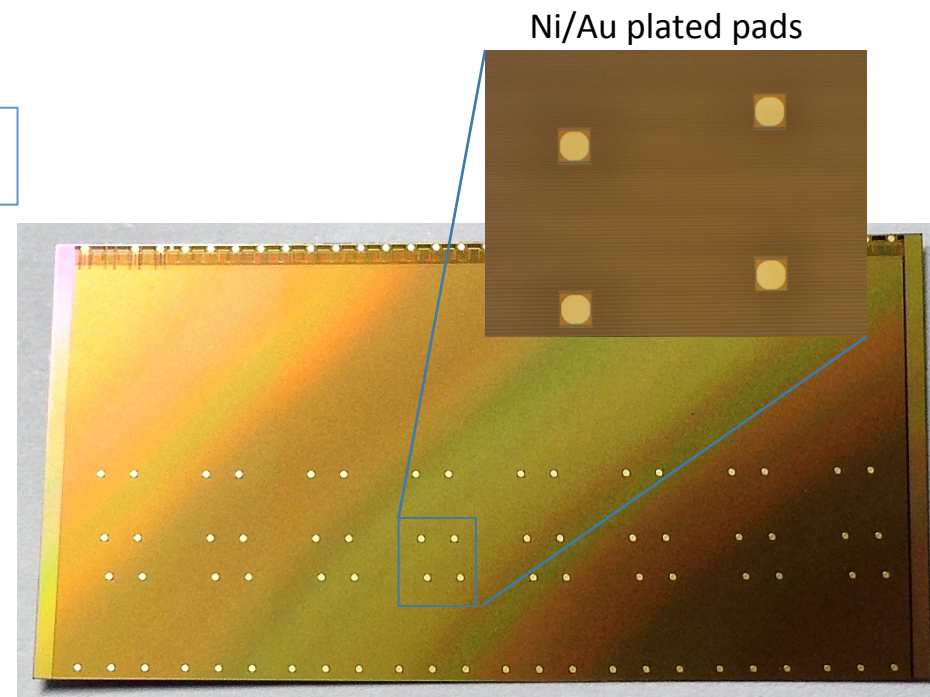
## Solder Pads

In order to solder the chip on the flexible printed circuit (FPC), the chip **Al pads need to be covered with Ni-Au** (wet-able surface)

Plating is done on wafers level using electroless Ni-Au plating, prior to thinning and dicing



ALPIDE-1  
(~15 x 30 mm<sup>2</sup>)



Ni/Au plated pads

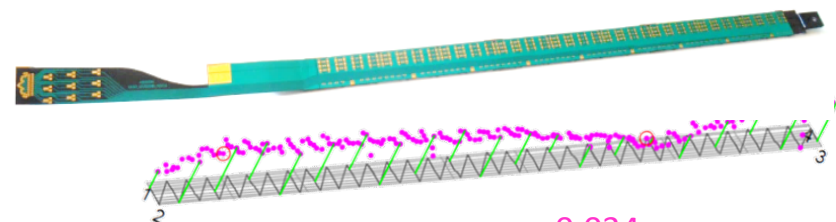
Contact pads are distributed over the matrix  
(custom designed)

# Inner Barrel Stave



## Stave HIC+ Space frame assembly

Dimensional accuracy

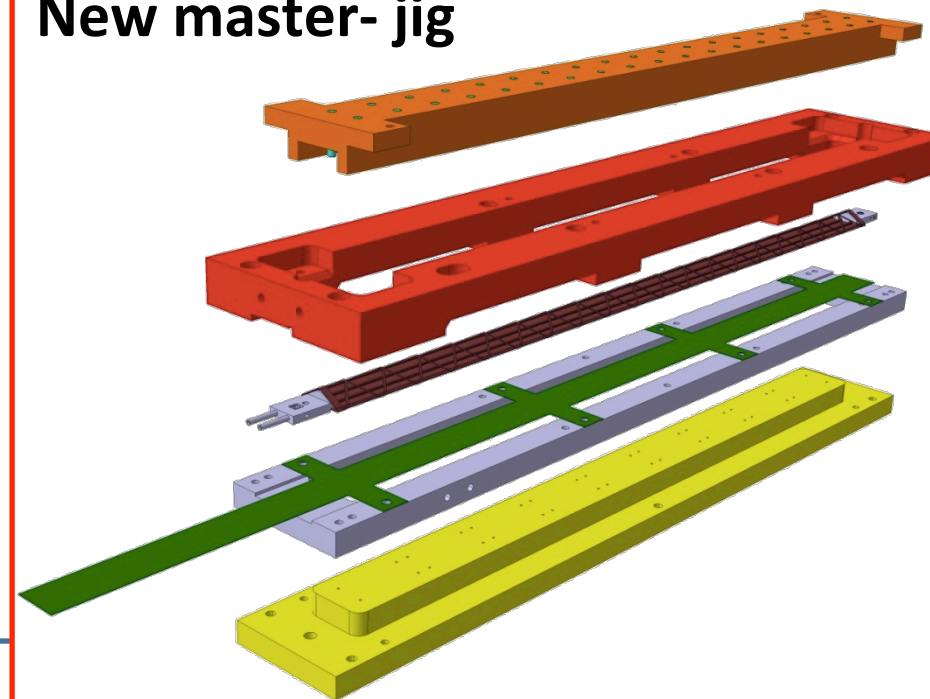


+0.034 mm  
- 0.034 mm

### status

New master jig (**ready**) will improve stave accuracy

## New master- jig



### ongoing

New master jig produced and shipped from the Company, metrological verification ongoing

## Space frame production

### status

Available : n. 20 spaceframe

### Ongoing

pre-production continues to prepare for final series production



Layout and curing process optimization: planarity achieved  $\pm 0,028 \div 0,040$  mm



# MAPS Geometry

from the pCDR:

Layer	radius (cm)	pitch ( $\mu\text{m}$ )	sensor length ( $\mu\text{m}$ )	depth ( $\mu\text{m}$ )	total thickness $X_0\%$	length (cm)	area ( $\text{m}^2$ )
1	2.4	28	28	50	0.3	27	0.041
2	$\sim 4$	28	28	50	0.3	27	$\sim 0.068$
3	$\sim 6-15$	28	28	50	0.3	$\sim 27-39$	$\sim 0.102-0.368$

3 layers will probably be needed to define the track position and curvature for a 2nd vertex reconstruction, can be done within the material cost of 1 VTX pixel layer

Similar inner layer positioning, just outside our beam pipe

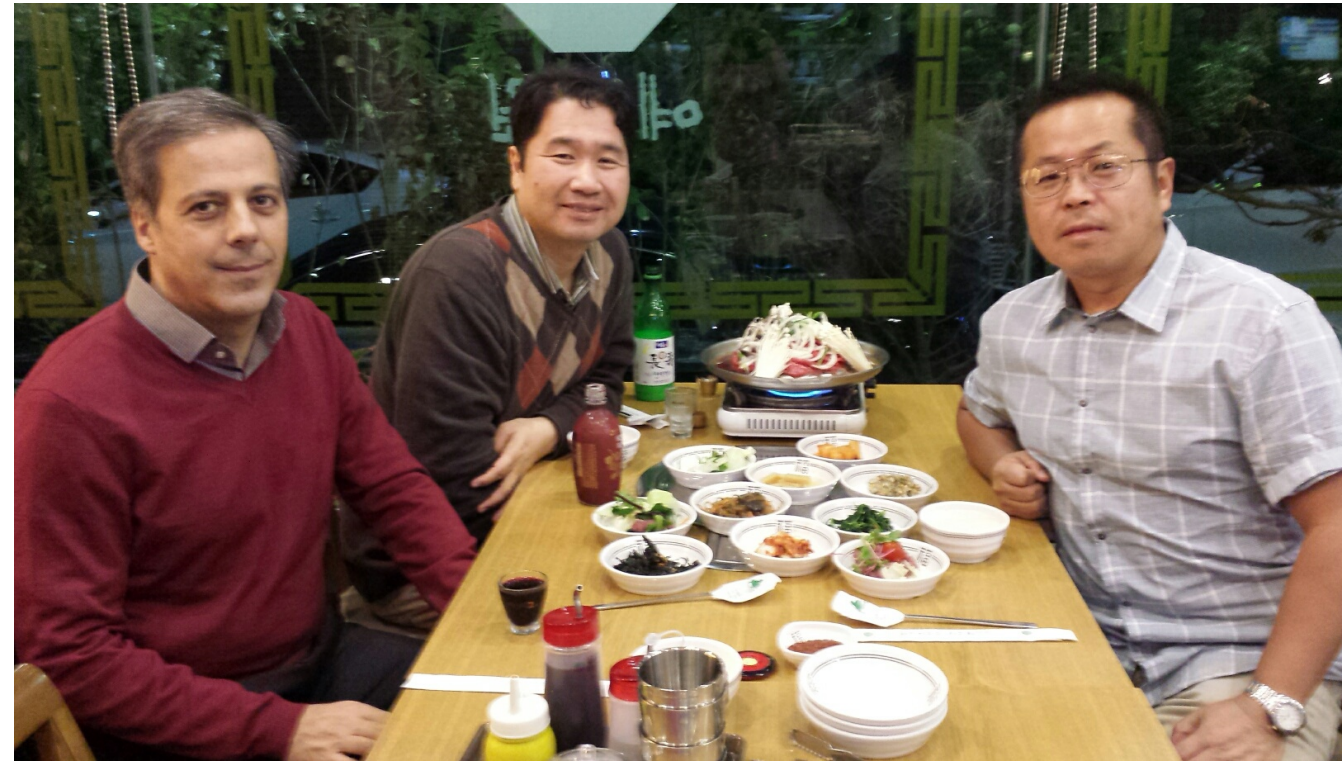
Outer staves could sit as far as 6 cm from the beam pipe before a longer than 27 cm ladder arrangement is needed—as dictated by vertex $\otimes$ eta coverage.

Optimizations between track position requirements and pattern recognition could force the outer layer out farther, depends on outer tracker design

We started with the more compact (2.4,4,6) version...

# Making the MAPS a Reality

- Had good discussions with Luciano Musa and Yongil Kwon in Korea during K/J sPHENIX workshop
  - CERN will provide a few chips with readout cards “immediately” for sPHENIX/LANL R&D
  - For the final sPHENIX project, share the R&D cost with ALICE (~\$2.5M) accordingly to the size of detectors (~\$250K?)
- Plan to visit Berkeley(or CERN) to learn about the operation, and get help from them to start R&D at LANL
- Possible collaboration with Korea institutes to provide MAPS chips for sPHENIX inner pixel detectors
  - Korea funds:
    - MAPS chips
    - Production test, assembly etc.
    - A few \$100K possible (new proposal)
  - LANL/US provide ROC/FEM
    - LANL LDRD/DR?
    - ~\$1M ? (take advantage of ALICE ROC design etc., minimal R&D)



sPHENIX inner pixel detectors:

$R = 2.5/4.0/6.0 \text{ cm}$

$Z = \pm 50 \text{ cm}$

$\text{Area} = 2 \cdot \pi \cdot R \cdot Z$

$= 7,850 \text{ cm}^2 = 0.8 \text{ m}^2$

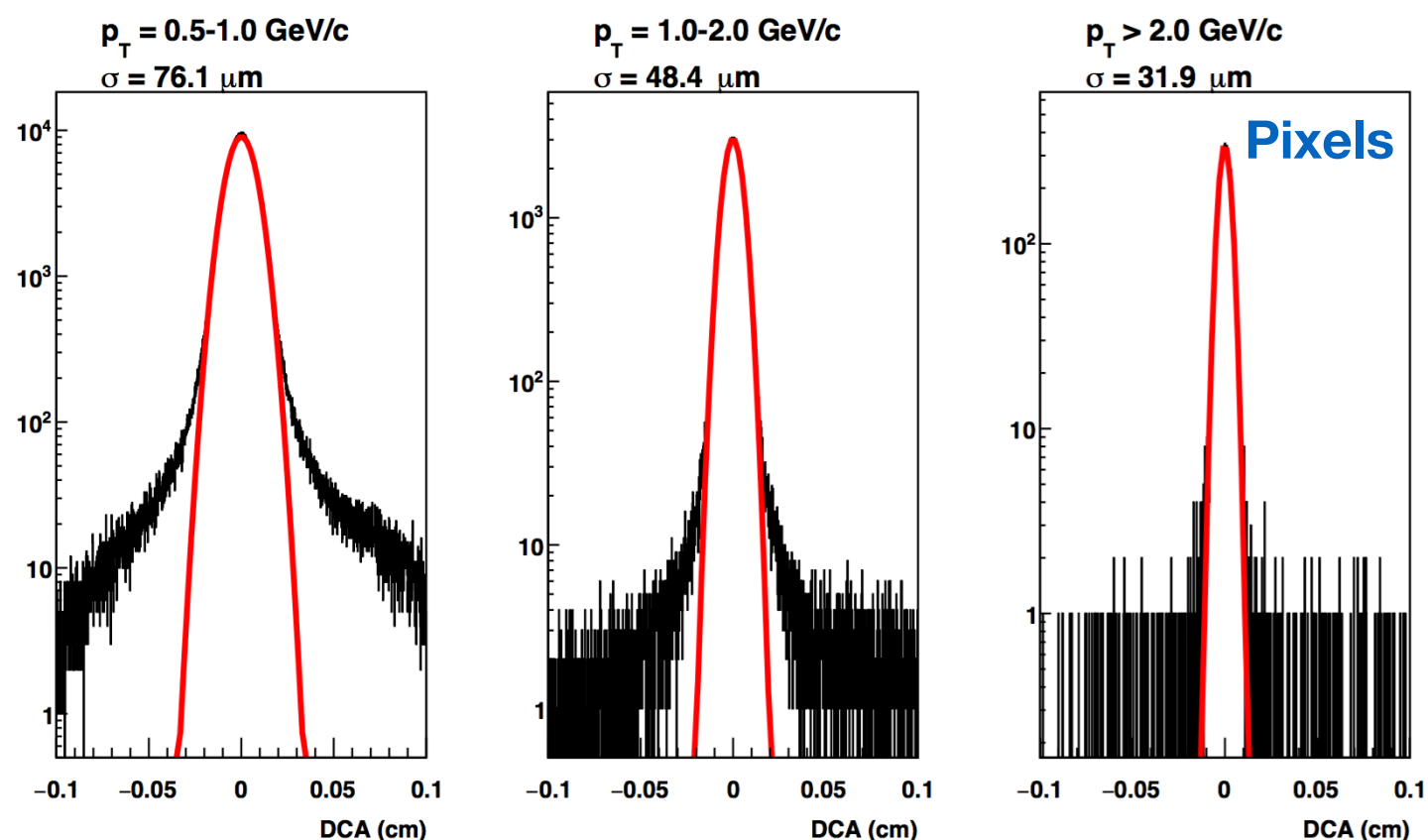
$\text{Chip} = 15 \text{ mm} \times 30 \text{ mm} = 4.5 \text{ cm}^2$

$7850/4.5 = 1750 \text{ chips}$

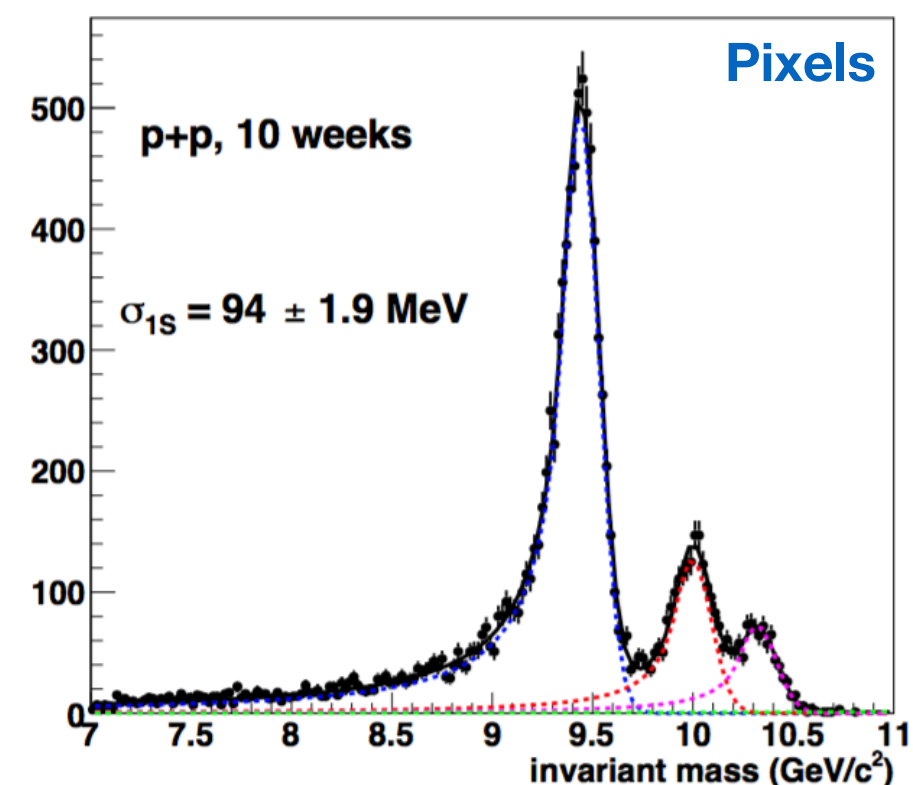
$\text{Wafer} = 48 \text{ chips}/\$2\text{K} \rightarrow \$73\text{K}$

# pCDR Performance Plots

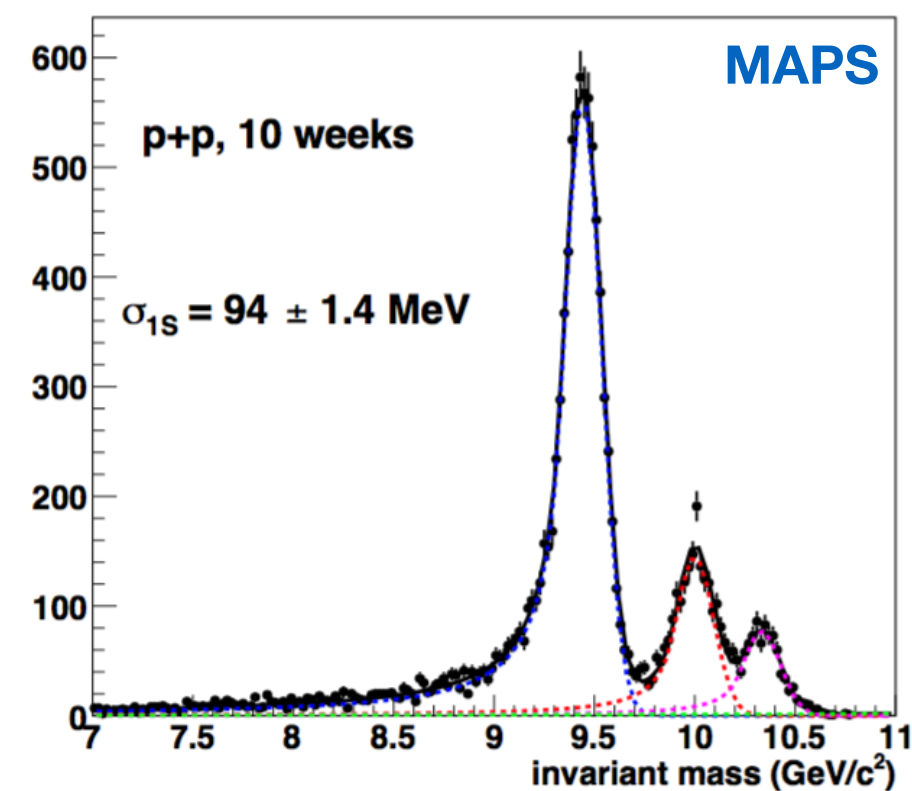
Thanks TF!



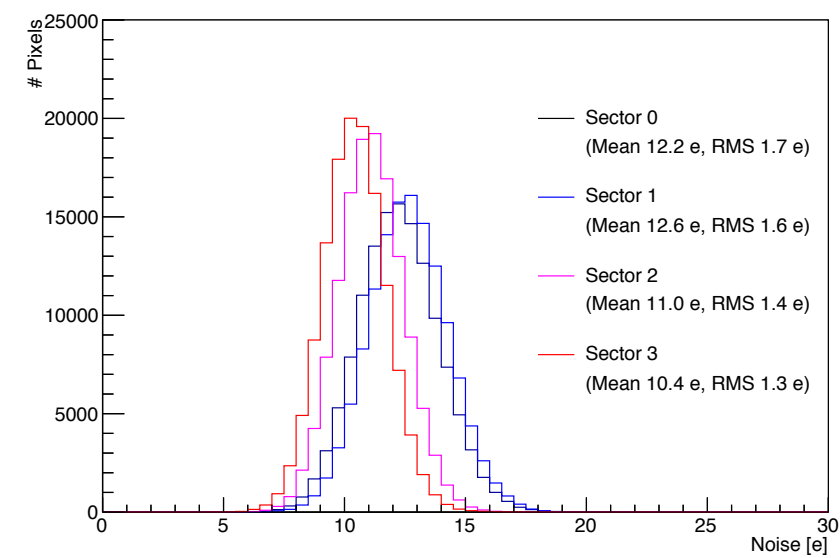
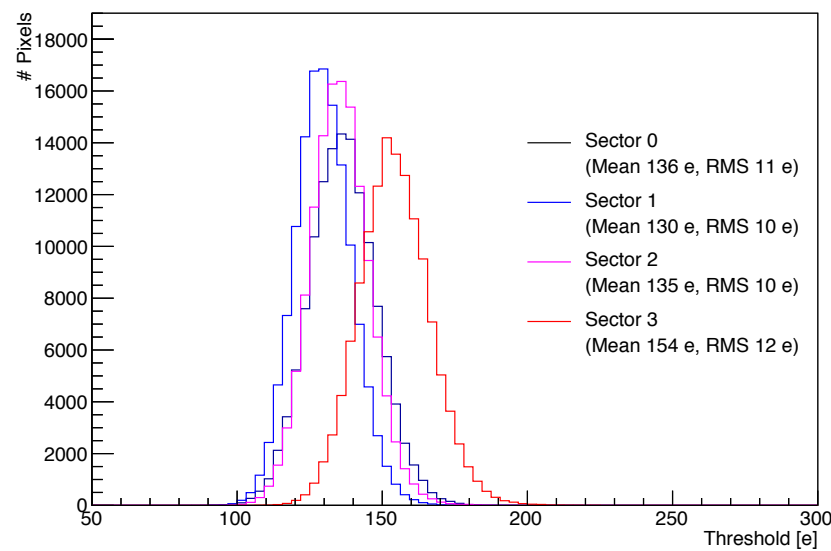
$Y(1S,2S,3S) \rightarrow e^+e^-$



$Y(1S,2S,3S) \rightarrow e^+e^-$



### Example of Threshold and Noise Distributions



$$V_{\text{SUB}} = -3\text{V}, I_{\text{THR}} = 0.5\text{nA}, V_{\text{CASN}} = 0.95\text{V}$$

- ▶ All sectors behave qualitatively similarly
- ▶ Noise is about the same value as threshold RMS
- ▶ Threshold about 10 x higher than noise
- ▶ Threshold 7 x smaller than most-probable energy loss signal of a MIP in 18 $\mu\text{m}$  of silicon



# Missing Detector Requirements

What does our Proposal and pCDR say about b-jet id:

**Heavy quark jets** The key to the physics is tagging identified jets containing a displaced secondary vertex

- precision DCA ( $< 100$  microns) for electron  $p_T > 4 \text{ GeV}/c$
- electron identification for high  $p_T > 4 \text{ GeV}/c$

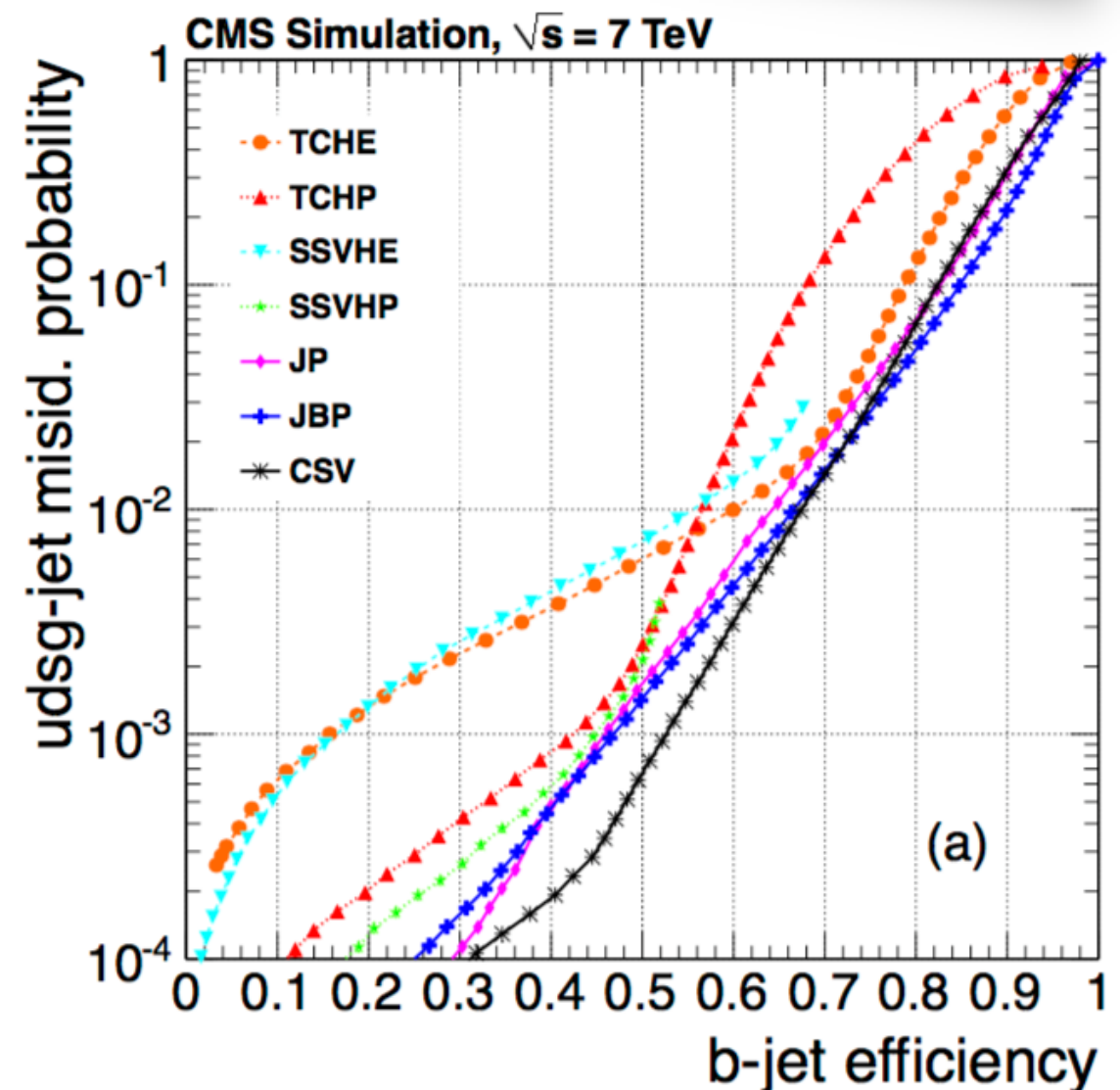
The current spec doesn't define a purity/efficiency requirement and focuses only on the semi-leptonic channel for some bizarre reason.

**We will need to add either:**

- (1) charged particle tracking efficiencies  
(3-track counting:  $\sim 95\%$  will be needed)
- (2) track position resolutions / better IP resolutions  
(2nd vertex CMS IP resolutions  $\sim 15\text{-}30 \text{ um}$ )  
(multi-DCA needs  $\sim 70 \text{ um}$ )

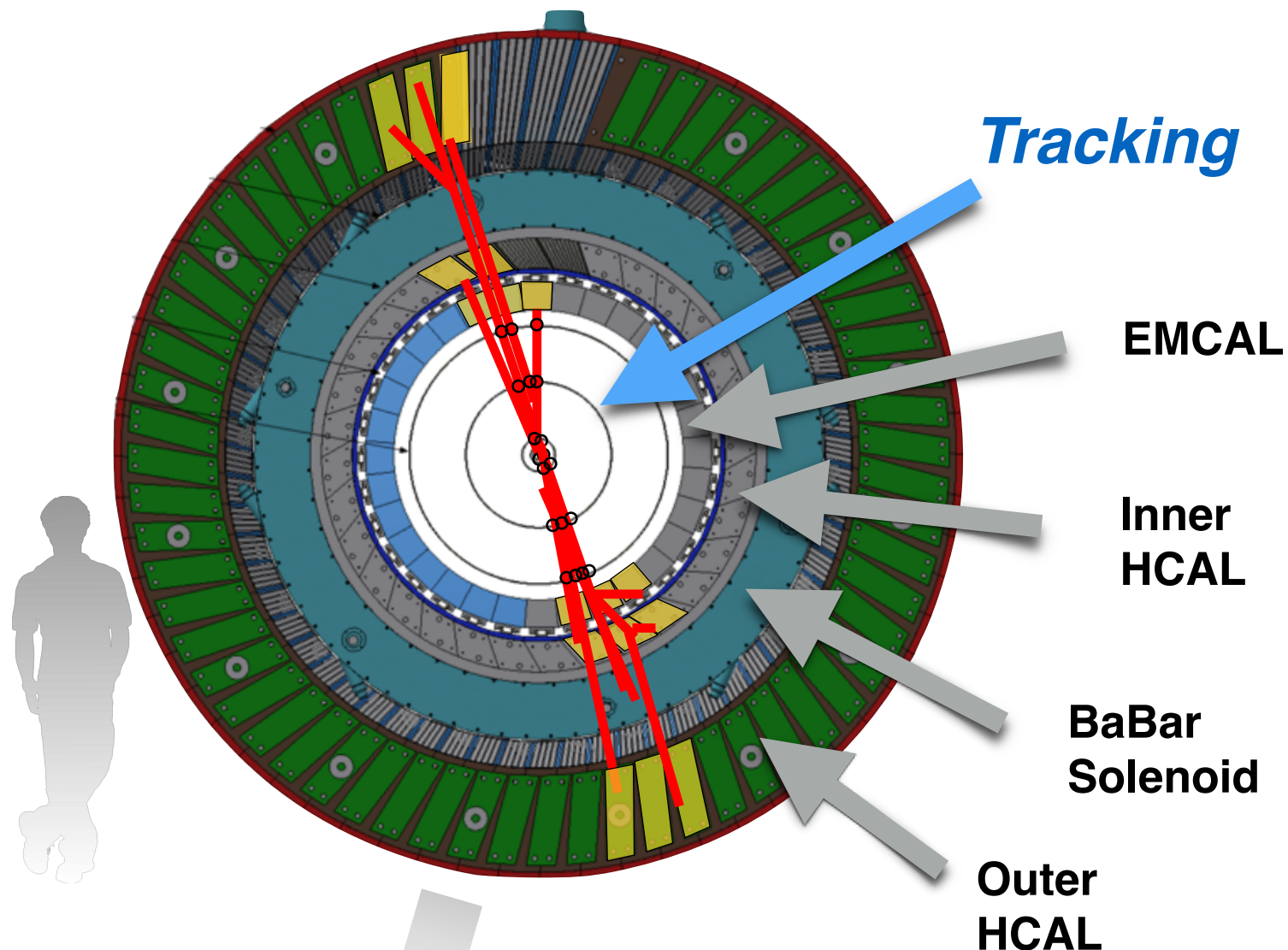
Or more generally, we should define a spec for:

- (A) B-jet identification purity (contamination) and efficiency requirement  
(We argued in April that:  
 $\sim 45\%$  efficiency and  $\sim 35\%$  purity in Au+Au would be comparable to CMS)



**It is a big (unavoidable) job to connect these different methods and the physics to detector requirements but we can use CMS-inspired numbers in the interim**

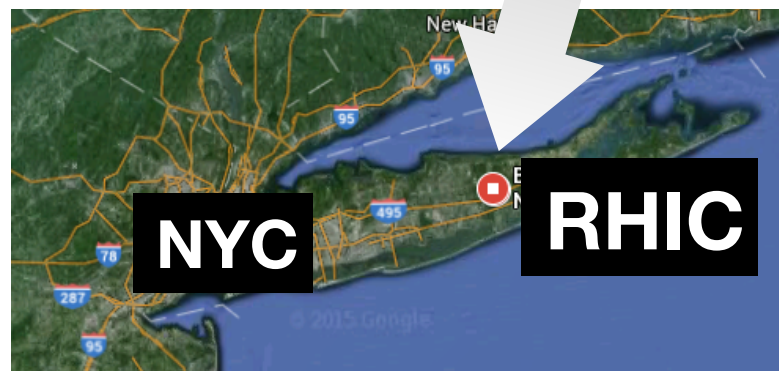
## Jets and Upsilons at RHIC in 2021 & 2022



**Physics:** study of QGP structure over a range of length scales and temperatures with **hard-scattered probes inc. bottom quark jets**

*“[sPHENIX] presented **a compelling physics program.**”  
~ sPHENIX DOE Science Review Committee*

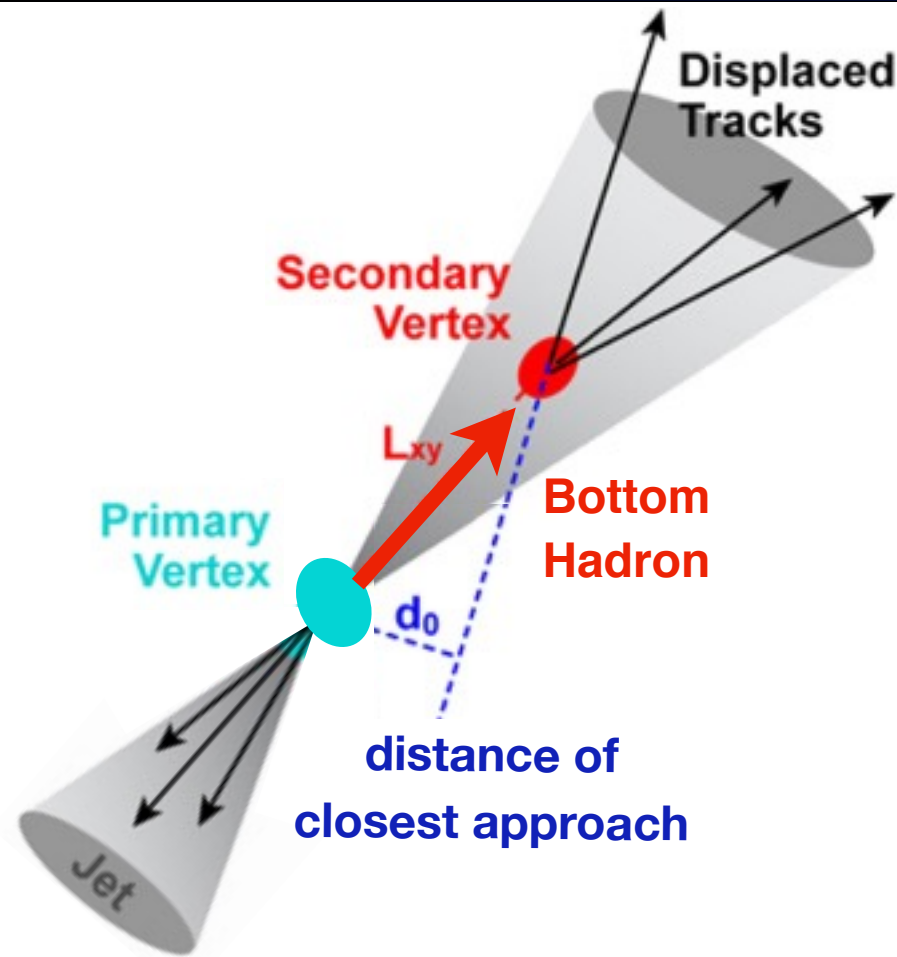
**sPHENIX highlighted in Hot QCD Long Range Plan**



*Inaugural Collaboration Meeting  
Rutgers Dec 10-12th, **~60 institutions***



# Impact of a LANL Contribution



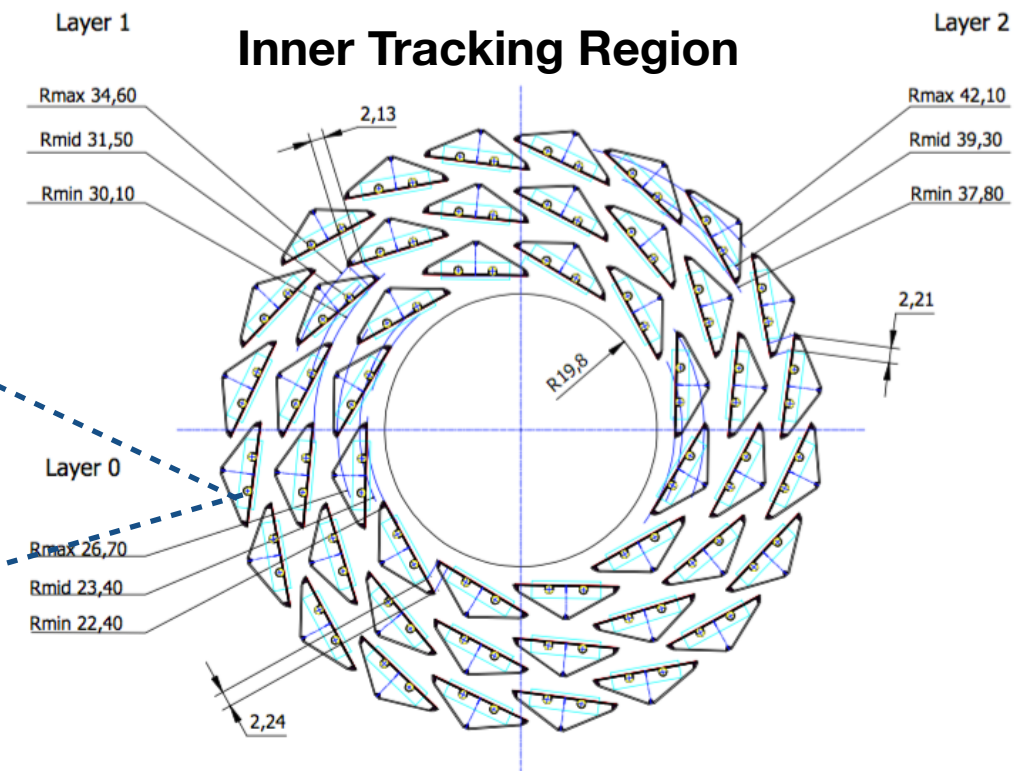
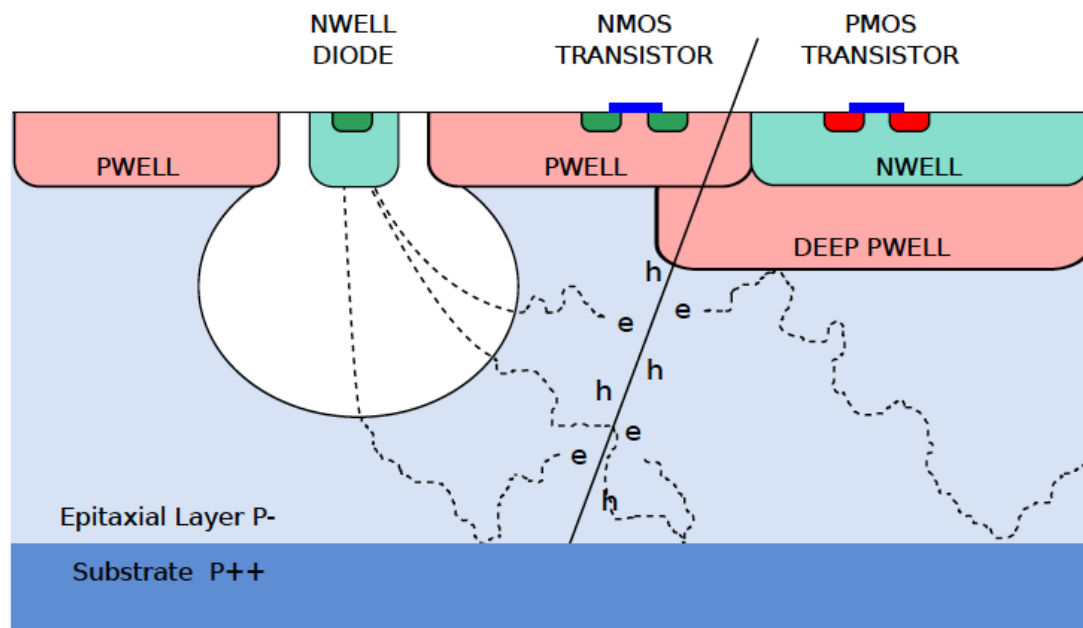
High Precision High Efficiency Charged Particle Tracker Needed by sPHENIX for Bottom Jet Identification

**P-25 expertise on silicon tracking** ideally suited for this role and sPHENIX project management craves LANL leadership

## Inner Silicon Concept with Monolithic Active Pixel Sensors:

Very fine pitch ( $<30 \times 30 \mu\text{m}$ ), large efficiency ( $>99\%$ )

Optimizations for material thickness,  $\sim 0.3\%/ \text{layer}$



**T-2 expertise on heavy quark and jet calculations** is needed to support this effort